ENVIRONMENTAL HAZARDS IN SMALL WATERSHEDS: FLASH FLOODS - IMPACT OF SOIL MOISTURE AND CANOPY COVER ON FLASH FLOOD GENERATION

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ABSTRACT. - Flood events in small mountain watersheds, called flash floods, have been documented rather frequently over the past decades. Floods of this type have also been reported from the hilly and low mountain catchments of Hungary. Prediction of flash floods is extremely challenging and requires the study of a plethora of environmental factors. Runoff models, such as the HEC-HMS, have been used to model floods on small (usually less than 200 km^2) watersheds. Among many others, one very important input parameter to the HEC-HMS model is the soil moisture content. In a 1.7 km^2 study watershed in SW Hungary, we have monitored the temporal and spatial changes of soil moisture with time domain reflectrometry (TDR) techniques. We conclude that soil moisture show a large spatial heterogeneity; however, the temporal behavior of soil moisture among the individual measurement points is extremely consistent.

Key words: flash flood, watershed, soil moisture, modeling, time domain reflectrometry

Introduction

Flood events in small hilly and low-mountain watersheds have become more frequent over the past decades in Hungary. According to the report of Environmental Protection Agency of the European Union, floods involve the largest economic loss in Europe. Over the period of 1998 to 2002, about 100 devastating floods caused 700 fatalities, evacuation of 25,000 people and an economic loss of 25 billion Euros. However, the majority of the losses are caused by „conventional" riverine floods, but, over the past decades, floods more frequently occur on small streams located in small (10 to 100 km^2) mountainous watersheds. This latter type of floods, appropriately named as flash floods in the English nomenclature, are typically triggered by extreme rainfall events in narrow watersheds with rugged topography. Flash floods are generated 0.5 to 5 hours after an event of intense rainfall and usually last for a few hours (in extreme cases up to a day). In certain cases, however, snowmelt may also contribute to the generation of flash floods, hence low-intensity rainfall, amid ideal environmental settings, may also trigger flash floods. A third, and recently more common, type of flash flood occurs in heavily urbanized areas, where there are extensive sealed horizontal surfaces. This latter type of floods is called urban floods or pluvial floods; however, some authors clearly differentiate them for conventional flash floods (Cobby et al., 2008).

Due to the geographical settings of western and northern Hungary, flash floods are everyday phenomenon and have been reported several times over the past decades. As the Carpathian Basin is surrounded by subalpine and Alpine Mountains in three directions, drainage to low elevation areas naturally trigger floods, when extreme atmospheric events occur. They are usually localized events; however, they may cause widespread and considerable economic losses (Lóczy & Juhász, 1996; Gyenizse et al., 2005). To minimize the magnitude of such economic and social impacts, a sophisticated and efficient prevention and warning system need to be developed. However, prediction of flash floods is rather challenging, due to the large spatial variation in the intensity of convective rainfall events and the mosaic and heterogeneous pattern of topography, land use and soil types. Furthermore, lead times to issue warning are extremely short, in the majority of cases they are measured in hours. In addition, prediction uncertainty is very high due to the available rainfall forecasting methods, and the localized character of the precipitation. To overcome these prediction problems, both field and model studies are required to contribute to our understanding on the generation of flash floods.

Flash floods, at least meteorologically, are characterized by the "too much water, too little time" approach. This descriptive term refers to the high-intensity, and usually high cumulative rainfall, and the above-mentioned short lead time. The hydrological approach, however, is somewhat more sophisticated, and simultaneously is more complex. Once again, rainfall is considered as the primary triggering factor of flash floods, but certain environmental boundary conditions are also regarded to be extremely crucial. These environmental factors include the canopy cover, soil thickness, soil physical properties, as well as topography. These environmental factors affect the time of concentration, and indirectly the prediction time lead.

Time of concentration is one of the pronounced differences between traditional riverine floods and flash floods. In the case of flash floods, the short time of concentration (ranging between 0.5 to 6 hours) makes risk analysis, prediction, prevention and evacuation extremely difficult. Flash floods also differ from conventional floods according to rainfall type. As we mentioned above, flash floods are primarily triggered by convective, high-intensity rainfalls, where the intensity may be further increased by orographic effects. Riverine floods, on the other hand, are usually preceded by multiple-day medium-intensity precipitation. Despite their non-seasonal dependence, the majority of flash floods, at least in Hungary, occur between March and mid-October.

The applied hydraulic models remarkably differ between the two basic types of flood. The primary difference is the area of the modeled watershed, which in the case of flash flood modeling covers a land area of usually 10 to 100 km^2. This watershed area is 1 to 2 magnitude less than in the case of riverine floods. As flash floods are results of the coincidence of several environmental factors, model softwares require a plethora of input data. In this case, not only the precipitation is essential as input data but the model also processes topographic data (digital elevation model, hereafter DEM), land use and land cover and various soil properties, such as infiltration rate and topsoil thickness.

Flash floods and climate change

One of the most debated, at the same time, the most serious environmental problem of the 21th century is climate change. Although the global nature of the problem is obvious, the general trend of the process is still unclear. Nevertheless, all predictions agree upon the fact that the frequency of extreme and unpredictable meteorological events has been increasing. Consequently, the temporal frequency of natural hazards and disasters, triggered by this type of extreme meteorological events is also on the increase. In Hungary, for instance, annual precipitation slightly decreased between 1960 and 1990, while the number of rainy days dramatically decreased. Consequently, the average daily precipitation on rainy days increased significantly, and presumably, the total accumulated precipitation per rainfall event also increased (Mersich et al., 2006). Moreover, winter precipitation is more frequently falls as rain, generating rain-on-snow type flash flood events in Hungary, predominantly in early and late winter.

Flash flood events in the world

The majority of documented and observed flash flood events have been reported from the United States. Every year, flash floods are responsible for more fatalities than any other meteorological phenomenon in the US. Based on the 30-year average, flood caused death toll totals 120 fatalities annually (NWS, 2004a). From 1996 through 2003, an average of 3000 flash flood events were documented annually (Davis, 2001). In comparison, the number of annually documented tornadoes totals about 1000, and is associated with 60 fatalities per year (Storm Prediction Center, 2004). Although some authors note that considerable improvements were employed in the US and in certain other countries (e.g. in the UK), flash floods are still among the most dangerous natural phenomena worldwide (BAMS, 2000; Davis, 2001). In 1972, for instance, 125 people were killed when a flash flood inundated a narrow valley in Buffalo Creek, West

Virginia (National Research Council, 2008). In the same year, 238 people died of flash flood in Rapid City, South Dakota when 380 mm rain fell within 6 hours (Davis, 2001) . One of the most thoroughly documented flash floods of all time occurred in the Thompson Canyon, Colorado, a small watershed (181 km^2) drained by one of the tributaries of the Colorado River. In 1976, 350 mm rain fell under six hours, flooding the narrow canyon and killing 139 people when the water level rose suddenly and unexpectedly by several meters (Davis, 2001).

Flash floods not only affected the United States but similar cases have been reported from Boscastle, England, UK, and Zelezniki, Slovenia (Kobold & Pogačnik, 2008). One of the largest flash flood events of recent years happened in Boscastle, southwestern UK (Cornwall Peninsula) on August 16, 2004. The entire rainfall event lasted for about seven hours, however very localized, total 24-hour cumulative rainfall in one location (Otterham) reached 200.4 mm. At the same time, other rain gages, located within a 10 km-radius circle around Boscastle, reported a cumulative rainfall between 46.7 and 184.9 (Met office, 2004). In places upstream from Boscastle, rainfall intensity reached 24 mm within a 15-minute period, while in Boscastle, 89 mm rain fell in an hour (Met office, 2004). The probability of such a high-intensity rainfall in Boscastle, at least according to the available statistical rainfall data, is 1 to 1,300. The intense rainfall was followed by a 2-meter water level rise, when the simultaneous discharge reached 140 m^3 per second, which means an estimated 400-year return time. During the Boscastle flash flood event, 100 residential homes were destroyed and 75 cars were swept to the sea. Due to the efficient assistance of the available rescue teams, no fatalities were reported from this disastrous flash flood event.

Flash flood events in Hungary

Several flash flood events were reported from the hilly regions of Hungary (e.g. Horváth, 1999, Koris and Winter, 2000; Ely et al., 2001; Szlávik, 2003,). However, due to widespread publicity of the conventional type floods of the rivers Danube and Tisza, the public awareness of flash flood events is limited in Hungary. The majority of flash floods were reported from southwestern Hungary (Western Mecsek Hills, watershed of the Bükkösdi-víz) and northern and northeastern Hungary (e.g. Kemence Stream, Kövicses Stream and the Csörgő Stream) (Figure 1). Largest rainfall intensity, at least since the initiation of regular measurements, was reported from Dad, northern Hungary. On June 9th, 1953, 220 mm rain fell 3 hours. This extreme rainfall generated a large flash flood on the Átalér and Váli-víz Streams, which swept away the railway line (Szilágyi, 1954). One the most thoroughly documented flash flood event of Hungary happened in Mátrakeresztes, on April 18, 2005. Once again, the flash flood that was triggered by a localized, convective, and simultaneously very intense rainfall event.

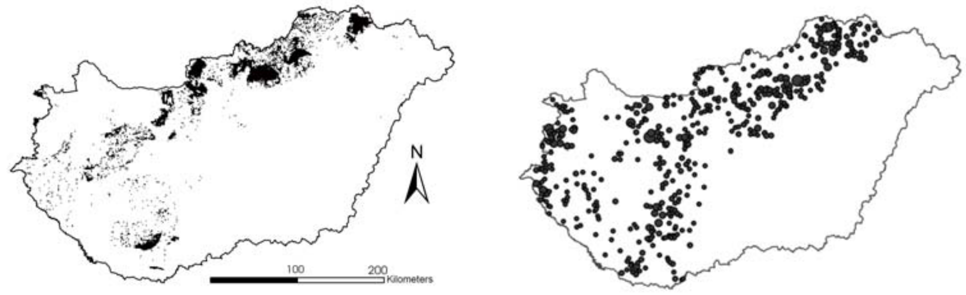

Figure 1. Left figure: Watersheds potentially flash flood-impacted (black dotted) areas simulated by our historical-statistical model; Right figure: Locations, from which flash flood associated damage and economic loss have been reported for insurance companies

Insurance claims associated with floods and extreme rainfalls in Hungary totaled 835 cases over the past 25 years (Szlávik & Kling, 2007, Figure 1), out of which 39 cases were considered typical flash floods. On June 27, 1987, for example, several houses and part of the railroad was swept away in the Bükkösd Valley (Mecsek Mountains, SW Hungary) when 71 to 88 mm rain fell over a 6-hour period (Eszéky, 1987; Eszéky, 1992). Flash floods caused traffic jams and overflown sewage systems when a rainstorm swept through the city of Győr (northwestern Hungary) on March 27, 2005. Perhaps the largest economic loss associated with flash floods was recorded in Mátrakeresztes (Horváth, 2005), when a flash flood inundated the valley of the Csörgő and Kövicses Streams on April 18, 2005. Economic loss was estimated to reach 1 billion HUF (approx. 5 million USD). The city of Kaposvár was flooded by the Kapos Stream on August 21, 2008 (Hizsák, 2005) when 105 mm rainfall fell in 3 hours. However, we need to emphasize that in terms of discharge flash floods of Hungary are not comparable with those documented from the Alps (e.g. Ranzi et al., 2007), although in terms of general characteristics, behavior and economic loss caused they bear a close resemblance with Alpine floods.

These latter examples appropriately illustrate that the occurrence of flash floods is predictable in Hungary, however very few studies have been conducted hitherto to identify the triggering factors which generate floods of this type (e.g. Szilágyi, 1954; Horváth, 1999, Pirkhoffer et al., 2007). Thus, we believe that the establishment of a flash flood guidance (FFG) system is unavoidable in order to prevent considerable economic loss, and perhaps death toll (Pirkhoffer et al., 2008). Such on-line flash-flood warning and alert system is already in operation in the United States, operated by the US National Weather Service and the National

Oceanic and Atmospheric Administration (Georgakakos, 1986; NOAA, 2008) and in the United Kingdom.

Hitherto, however, Hungary does not have such a nationwide flash flood warning system. The primary objective of the present study is to delineate, from the viewpoints of meteorology, hydrology, land use and topography the most flash flood-prone areas of Hungary, i.e. a development of a historical-statistical model to predict the most flash flood prone areas in Hungary (Czigány et al., 2008). Within the framework of the Jedlik Ányos project, we plan to employ a rapid screening method to identify the most flood-impacted watersheds of Hungary, and to compare this with the available historical data. Critical threshold runoff values and critical cumulative rainfall amounts will be determined for these watersheds for various environmental scenarios. This goal forms an integral part of the overall objective, i.e. the development of a nationwide flash flood warning system of the Jedlik Ányos project.

Objectives

In the present paper we primarily focus on the results of the soil moisture monitoring program and secondarily on canopy survey. Soil moisture was measured with the time domain reflectrometry (TDR) technique, using a TDR 300 instrument from Spectrum Technologies Inc. (Plainfield, Illinois, USA) equipped with 20 cm long electrodes. 10 measurements were taken at each location within a radius of 1.5 meters. Data was then averaged and processed in ArcGIS 9.1. software environment and, afterwards, spatial and temporal heterogeneity was analyzed. To interpolate raster data, the inverse distance weighted function was employed This preliminary data, alongside with other non time dependent data were used to create the base of the flowchart model that will be used for the development of the nationwide flash flood warning system. The secondary objective of the present study includes the effect of canopy and interception on soil wetness. This objective was achieved by taking photographs from the center of each monitoring station vertically upward. Photos were then converted to black and white, and canopy covered regions (in per cent) were calculated by using Adobe Photoshop CS software.

Monitoring of flash flood events in Hungary: Materials and methods

To achieve the above stated goals, we aimed at monitoring the temporal environmental variables that are required as input parameters for our modeling program, the HEC-HMS. This runoff model was developed in Davis, CA, United

States, and have been used widely for modeling runoff on relatively small mountainous watersheds (e.g.: Schindler, 2006). The three temporally variable parameter we monitored are the followings:

a) Precipitation
b) Soil moisture
c) Stream discharge

Precipitation and soil moisture were monitored at 14 locations in the small western watershed of the Sás Stream (tributary of the Bükkös Stream), SW Hungary. The catchment of the Sás Stream covers a land area of 7 km^2 and is bordered with slopes generally exceeding 20^{o}. The 14 monitoring stations are located on the smaller western watershed of the Sás Stream watershed, covering a mere 1.7 km^2. Both the Sás Stream and the Bükkös Stream are extremely prone to flash floods. Due to its rugged watershed topography, the Sás Stream is the major water supplier of the trunk river during the Bükkösd Stream's flood events. The valley of the Bükkösd Stream, upstream from the confluence of the Sás and Bükkösd Streams, have been inundated by flash floods in e.g. 1954 and 1987 *(Vass, 1999)*. During these events several houses were destroyed and railroad sections were swept away (Eszéky, 1987).

Results

TDR based soil moisture measurements indicate large spatial heterogeneity in the study catchment. This spatial heterogeneity is likely caused by several environmental factors in the relatively small watershed. These factors include (i) spatial variance in soil physical properties, (ii) spatial heterogeneity of canopy cover, (iii) slope variance, (iv) aspect, and (v) elevation.

Soil physical properties significantly vary within the 1.7 km^2 watershed (Figure 2). The lower elevation areas in the north are mostly covered by alluvial sediments, completely lack coarse fragments and usually maintain high soil moisture contents (shown with ID number 1 in Figure 3). Monitoring station number 2 is located in sandy soils, and values here are reflected in below average soil moisture contents (Figure 3). Medium elevation areas (between 185 and 250 m a.s.l) are predominantly covered by brown forest soils with clay illuviation (Alfisols in the USDA nomenclature). At higher elevations (250 to 600 meters) soils contain a significant amount of coarse fragments, and soil moisture is lower, in general, than at low elevation. Soil moisture content across the measured and interpolated area increases to the northeast and lower elevation. Thus, aspect may affect soil moisture content, as eastern slopes receive less irradiation than western slopes. Slope steepness also influences the ratio of infiltration to surface runoff.

Here in the watershed of the Sás Stream, steepness, in general, increases with increasing altitude. Besides the changes of physical soil type, steeper slopes then may contribute to decreasing soil moisture at higher elevation. It is also noteworthy, that at different measurement times (in weekly intervals) soil moisture content behaved very consistently among the individual measurement points (Figure 3). Soil moisture content ranged between 5.4 and 40.5 m^3 m^{-3} on September 12, 2008, between 18.9 and 44.8 m^3 m^{-3} on September 19, 2008, and between 16.6 and 45.5 m^3 m^{-3} on September 26, 2008. However, the broad range measured over the small 1.7 km^2 watershed is remarkable.

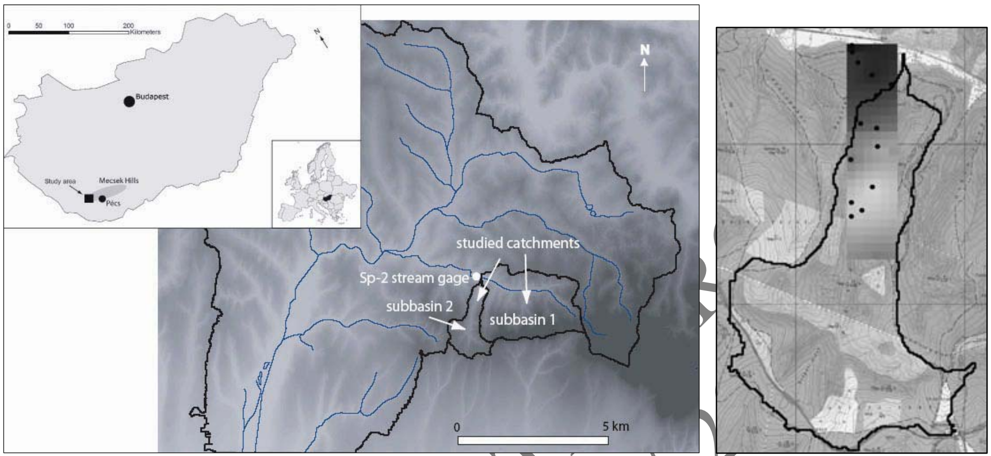

Figure 2. Location of the watershed of the Sás Stream (left figure) and soil moisture spatialheterogeneity among the 14 measurements point of the Sás Stream watershed (measure dand interpolated data, right figure, areas with higher moisture content are shown in deep black).

Nonetheless, soil moisture is a highly variable and challenging input parameter for the HEC-HMS runoff model, due to its considerable spatial heterogeneity. In the case of the HEC-HMS, for each watersheds, regardless their land area, only one soil moisture value is provided and, consequently, that does not reflect the above described spatial variance.

The second environmental factor we focused on during our field studies is the canopy cover. Canopy cover and interception directly influences surface runoff, as it delays throughfall and, consequently runoff. The watershed of the Sás Stream is heavily forested and is mostly covered by hardwood forests, with the predominance of oak, beech and hornbeam with occasional human interventions (forest roads, clearcuts and huts). Canopy cover ranged between 36.82% and 77.60% among the 14

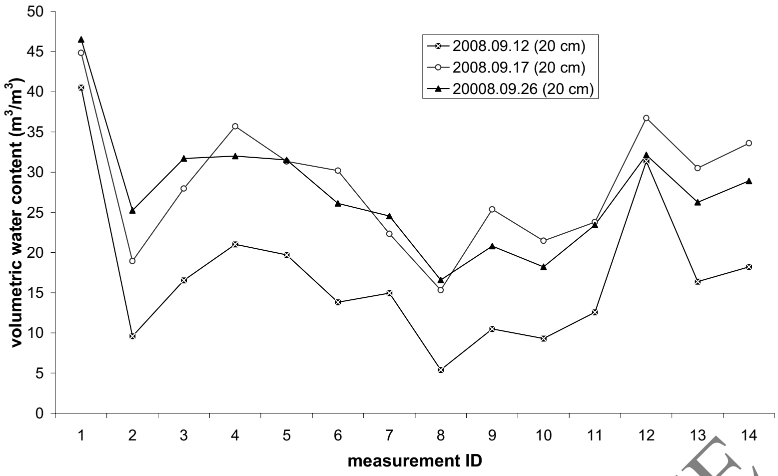

Figure 3. Temporal characteristic of soil moisture at the 14 monitoring stations measured at three different times. Note the consistent behavior of soil moisture.

monitoring stations on September 26th, 2008. The correlation between soil moisture content and canopy cover was very poor with a correlation coefficient of 0.1381 (Figure 4). This low correlation unambiguously shows that soil moisture is influenced by a range of environmental factors that all need to be considered when the environmental impact of soil moisture on surface runoff is studied.

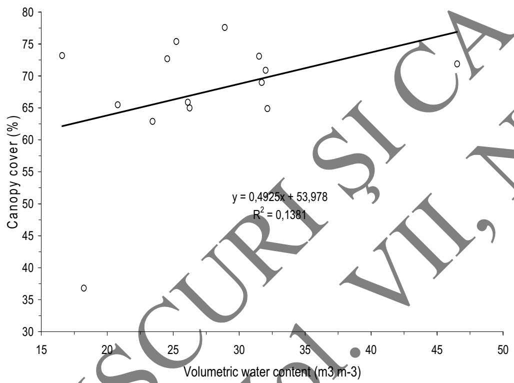

Figure 4. Left figure: Relationship between volumetric water content and canopy cover at the 14 monitoring points of the Sás Stream watershed. Note the poor correlation between the two environmental parameters. Right figure: Typical canopy cover in the heavily forested watershed

Conclusions

Based on filed studies and our formerly published historical-statistical model (Czigány et al., 2008) we determined the possible scenarios of a flowchart-based warning system (winter scenario is shown in Figure 5). The flowchart model is based on numerical simulations when precipitation threshold values are determined for the individual watersheds. Our field studies indicated that physical soil type influences model outputs considerably. Thus, our scenarios are classified according to various soil moisture contents, i.e. defined at 25%, 50% 75% and 100% saturation levels. By studying the relationship between canopy cover and soil moisture we need to conclude that precipitation is not the only factor which influences soil moisture. For instance, a cumulative precipitation ranged between 13.6 and 14.6 mm was measured for a single event (September 26, 2008) at the 14 monitoring stations. Despite the uniform spatial distribution of rainfall, soil moisture ranged between 16.6 and 45.5 $m^3\ m^{-3}$. The primary goal of the flowchart-type warning system is to issue warnings with at least a 3-hour time lead for watersheds where no adequate monitoring system is available.

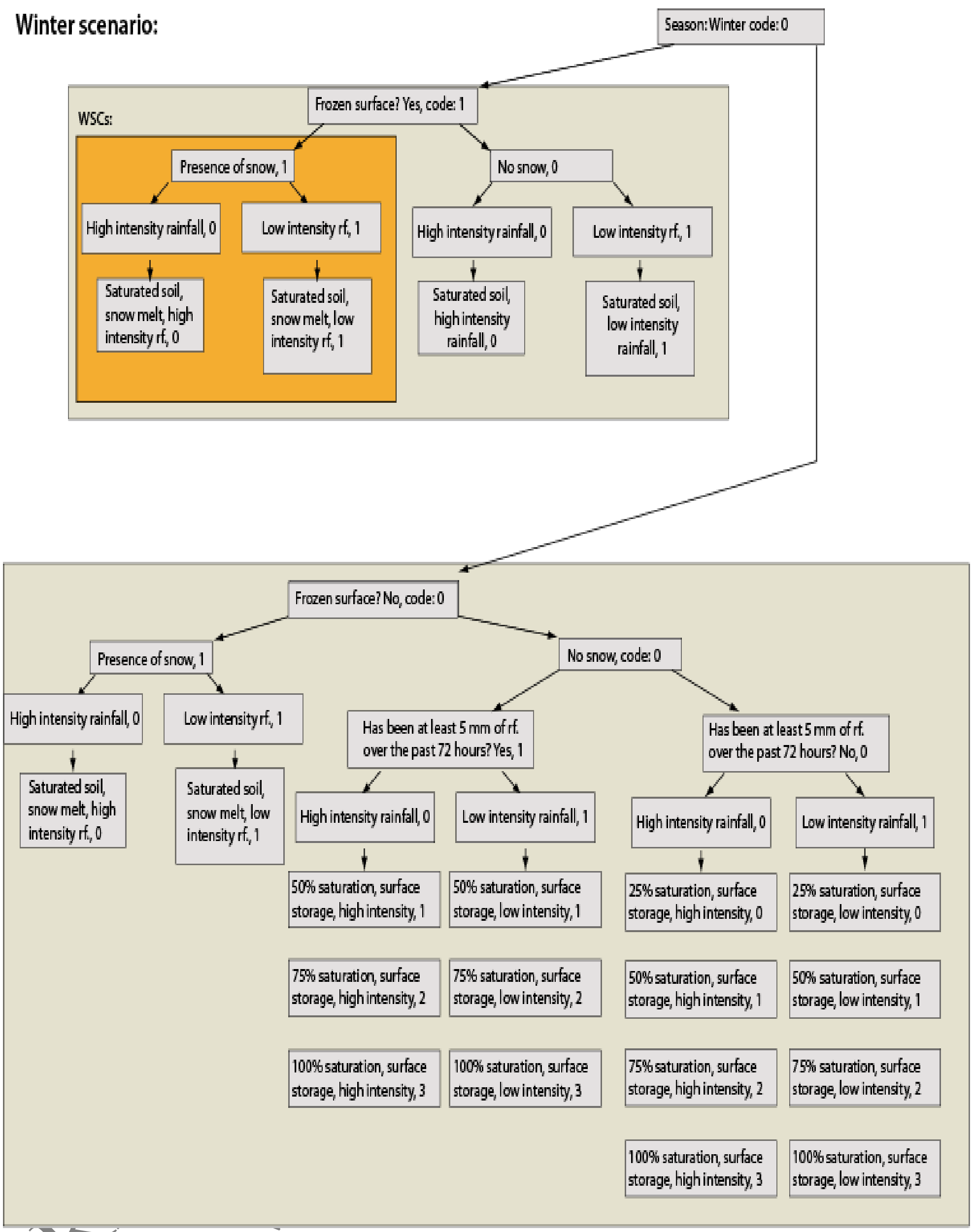

Figure 5. Schematic flow chart model of the winter scenarios developed for the nationwide flash flood warning system

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