

Background and Supporting Information for Post-Wildfire Risk Assessments in BC



Prepared for

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Cover photo: Dwain Boyer, B.C. Ministry of Environment, Nelson

BACKGROUND AND SUPPORTING INFORMATION FOR POST-WILDFIRE RISK ASSESSMENTS IN BC

1.0 INTRODUCTION AND PURPOSE

The purpose of this document is to provide the supporting information and rationale for the development of a post-wildfire risk assessment procedure for natural hazards. The procedure is presented in an accompanying document, *“Risk Assessment of Post-wildfire Natural Hazards”*. This background report references any similar procedures used by other agencies in their determination of post-wildfire hazard potential, summarizes techniques used to assess burn severity and water repellency, and provides a brief overview and summary of wildfires that have caused severe surface erosion, landslides, gully processes or flooding in the southern interior of BC and similar areas.

While the majority of wildfires in BC occur away from populated centers and infrastructure, a small number (referred to as interface wildfires) do have the potential to pose a risk to public safety, private property and infrastructure located within and downslope from the burned area.

To address potential post-wildfire hazards associated with these interface situations, the BC Ministry of Forests, Southern Interior Forest Region (SIFR) has developed a *Risk assessment Procedure* for post-wildfire natural hazards. This procedure is part of the SIFR's proposed Standard Operating Procedure (SOP) – *“Management of Increased Risk from Natural Hazard Events following Wildfires”* that has been prepared to respond to identified high risk situations involving public safety, private property and infrastructure.

Although this procedure is currently limited to the assessment of the risk of post-wildfire natural hazards, it could be applied to assessing natural hazards resulting from other causes as well.

For the purpose of this report, risk is defined as the chance of injury or loss, and is a measure of the probability and the consequence of an adverse effect to health, property, the environment, or other things of value (adapted from CSA 1997).

What are the post-wildfire hazards and risks that are of concern? In simple terms, the likelihood of occurrence of hazardous events such as severe surface erosion, landslides and floods can increase, sometimes significantly following a wildfire. This may pose a significant risk to public safety and/or damage to downslope property and infrastructure.

The procedure sets out general guidance for practitioners conducting the hazard and risk analyses. It will not determine if a risk is acceptable or tolerable, nor will it offer options for risk control or site works.

In the application of this procedure, users should exercise professional judgment when completing the tasks. As such, the application of all or some of the steps outlined in the procedure may vary depending on the circumstances. The procedure specifies tasks that should be performed by qualified professionals to meet the standard of care that is dictated by the downslope risk.

The procedure may also be used to assist the SIFR in establishing the scope of work for consulting contracts in a busy wildfire season.

1.1 Why is a Risk Assessment Procedure Required?

During the 2003 season several wildfires were interface events that posed a threat to public safety, infrastructure and private property either within or downslope from the burned area. Some interface wildfires had occurred previously in the southern interior (e.g. the 1994 Garnet fire in Penticton and the 1998 Silver Creek fire in Salmon Arm);, however, there had been limited effects on public safety, private property or infrastructure associated with post-wildfire hazardous events.

Following a short-duration, high-intensity rainstorm in October 2003, debris floods and flooding were triggered in several watersheds burned by the Okanagan Mountain Park fire (2003). These events damaged homes and infrastructure within the City of Kelowna.

In the summer of 2004, climatic events triggered hazardous events from several of the remaining interface wildfires from the 2003 season. These included:

- The Cedar Hills fire near Falkland – June 25 - Debris flows and debris floods followed a localized short duration-high intensity rainstorm. Highway 97 was temporarily closed, and two residences were damaged as well as other effects on private property.
- The Vaseux fire near Okanagan Falls – June 30 – Flooding and debris flows followed a short duration-high intensity rainstorm. Highway 97 was temporarily closed and several secondary roads were washed out. Minor damage to private property was also noted.
- The Mt. Beaven fire near Cherryville – July 6 – Several debris flows were triggered by a rainfall event; Several logging roads were impacted.
- The Strawberry Hill fire near Kamloops – July 20, August 4 – Debris flows followed a short duration-high intensity rainstorm. Minor damage to private property was noted.
- Kuskonook Creek fire near Creston – August 6-7 - A 30,000 m³ debris flow was triggered following a short duration-high intensity rainstorm; two buildings were destroyed, another damaged and Highway 3A was closed for several days by this debris flow.
- The Lamb Creek fire near Cranbrook – August 19 - A debris flood/debris flow was triggered in Gold Hill Creek (a tributary to Lamb Creek) following a short duration-high intensity rainstorm; two logging roads were washed out by this event, and the water quality of Moyie Lake was impacted.

In October 2005, following a prolonged rainfall (possibly a “rain on snow” event), several large debris flows were initiated in gullied streams on the slopes burned by the Ingersoll fire (from the 2003 season) near Nakusp. These events washed a forest road in several places.

Fortunately no lives were lost or injuries occurred in these post-wildfire hazardous events, although considerable property damage did occur.

Under the risk assessment procedure, wildfires will be screened to identify those that are located on slopes above populated areas, private property, or infrastructure (i.e. interface fires), or are located in a watershed draining into interface areas, and are

sufficiently large to be of concern. These fires will be assessed using this risk assessment procedure to ascertain the level of risk, as previously defined, following the fire.

In the 2003 season there were approximately 2,500 wildfires reported in BC. Of this total, it is estimated that perhaps a dozen would have been identified as wildfires of concern, that would have been assessed using this procedure (had it been available at that time).

2.0 POST-WILDFIRE RISK ANALYSIS PROCEDURES USED IN OTHER JURISDICTIONS

The development of the post-wildfire risk assessment procedure for BC is based on the best available science and experience of others working on this issue. It was the intent of the working group developing this procedure to review available examples of post-wildfire risk assessments and to take the most applicable information and incorporate it with experience gained in BC to develop the procedure for the Southern Interior Forest Region.

The Burned Area Emergency Response (or BAER) procedures and experience (developed and operated by the US Federal government) proved to be the best source of established and proven information. The BAER program was initially developed in the 1960s in response to the National Historic Preservation Act of 1966 that required the preservation of heritage and cultural resources on federal lands. Since then, the US Forest Service and other federal agencies have continued to develop and refine techniques for burned area assessments. The Interagency Burned Area Emergency Response Handbook (2005) can be viewed at <http://www.nps.gov/policy/DOrders/DraftHandbook.htm>.

During the development of the BC procedure, meetings were held with US Forest Service staff (at the Rocky Mountain Research Station in Idaho) to discuss their experience in developing and applying the BAER procedure. Discussions were also held with other US government personnel with BAER experience.

A limited review of the assessment of the post-wildfire risks elsewhere suggests that there are no established procedures, other than the BAER procedure, for assessing the increased likelihood of flooding and severe erosion and the risks associated with these hazardous events following a wildfire. There is however a growing awareness of these hazards and risks at the local government level in some areas. For example, the authorities involved in the reforestation work following the prolific wildfires in the summer of 2005 in Portugal and Spain considered the possibility of post-wildfire flooding and erosion during the development of reforestation plans.

3.0 ASSESSING BURN SEVERITY AND WATER REPELLENCY: HOW HAVE THE VEGETATION COVER, FOREST FLOOR AND SOIL CHANGED WITHIN THE AREA OF CONCERN?

Many watersheds in the southern interior are affected by naturally occurring hazardous events (i.e. flooding, landslides, debris flows/debris floods and erosion). Wildfires can increase the frequency and magnitude of these events by reducing the forest and surface cover and altering the properties of surface soils. These changes to the vegetative cover and to the soils are of primary importance (along with rainfall intensity) when considering how the natural likelihood of these hazardous events has been altered following a wildfire. The assessments recommended in this procedure will establish how

watershed conditions have changed following a wildfire. Subsequent steps in the procedure will determine how the changes have impacted the probability (or likelihood) of occurrence of these hazardous events and what is the associated risk is to the identified elements. The following sections outline those post-wildfire changes to (i) vegetation cover and (ii) to the forest floor and soils that are of particular significance to watershed hydrogeomorphic response.

3.1 Post-wildfire changes to vegetation

Loss of the forest canopy, understorey tree and shrub layer, and in some fires, the loss of the large wood component (i.e. trunks, stems) is the most obvious changes to the watershed following fire. Wildfire effects on forest vegetation range from fires that only impact the understory vegetation through to stand replacing fires, or a combination of these extremes (USDA 2005). The wildfire regime and its impact depend on many factors such as fuel load, terrain, antecedent moisture and weather. The degree of vegetation loss can be subjectively described by a vegetation burn severity index, with the index ranging from unburned to high. An example of a vegetation burn severity index for forest, shrubland and grassland fires is given in USDA (2005). The vegetation burn severity index selected for the BC procedure is as follows:

Vegetation burn severity index from Curran et al. (2006) "*Large-scale Erosion and Flooding after Wildfires: Understanding the Soil Conditions.*"

Unburned	
Low	canopy unburned, trunks partially burned, understorey lightly or patchily burned
Medium	trees burned and dead, scorched needles remain, understorey burned
High	trees blackened and dead, needles consumed, understorey burned

Table 1. Vegetation burn severity index.

3.1.1 The significance of vegetation changes to watershed hydrogeomorphic response

The reduction in vegetation cover by a wildfire can cause:

- a reduction in moisture storage capacity by the vegetation;
- reduced protection of the soil from overland flow and erosion;
- reduced interception of precipitation;
- reduced evapotranspiration; and
- increased snow accumulation when the canopy is destroyed.

The key questions that a vegetation burn severity assessment should answer are;

- what is the reduction in surface vegetative cover? and,
- what is the potential for needle cast? (which can store moisture and provide erosion protection).
- how lethal to the vegetation was the fire, including an assessment of possible vegetation recovery

Vegetation burn severity can be assessed visually during a flyover, by ground truthing the watershed, or with aerial photographs using a vegetation burn severity index (e.g. USDA 2005). As an alternative to visual assessment, remote sensing satellite imagery can be used to assess vegetation burn severity. In the United States, the BAER programme has a dedicated remote sensing and GIS centre in Salt Lake City known as the *Remote Sensing*

*Applications Center*¹ or RSAC. This centre is able to rapidly provide the BAER teams with maps of burned areas. The SIFR is currently investigating the provision of maps of burned areas based on remotely sensed data through Selkirk College.

3.2 Post-fire changes to soils and the forest floor

Wildfire can alter the physical, chemical and biological characteristics of the forest floor (litter and duff layers) and the underlying mineral soil. A detailed review of these changes is provided in USDA (2005). Further discussion pertinent to the SIFR is provided in Curran *et al.* (2006). The effects of fire on soils are summarized as the 'soil and forest floor burn severity'. Some confusion exists in the use of the term 'burn severity' as it can be used in relation to timber or vegetation mortality, ecological effects or to indicate severity relative to historical fire events (Parsons 2003). For clarity, in this report it is either prefaced by 'soil and forest floor' or 'vegetation'. For the purposes of this procedure, soil and forest floor burn severity is defined as fire-induced changes in soil characteristics that affect the soil hydrologic function or soil erodibility, therefore possibly leading to slope and hydrologic hazards. Although the organic forest floor layer (litter and duff) is an intrinsic part of the soil system, because it functions somewhat differently from the mineral soil component, it is included in the title.

Post-wildfire changes in soils of particular relevance to the soil hydrologic function and soil erodibility include Parsons (2003):

- loss of forest floor cover ;
- loss of soil structure, organic matter and shallow roots in the surface layers of the mineral soil;
- development of an erodible ash layer; and
- development of soil water repellency.

(Note that other effects of fire on soils, such as the destruction of seed banks within the soil, which have long-term implications for catchment response, are not considered here.)

These changes can:

- increase soil erodibility;
- decrease moisture storage capacity;
- decrease soil permeability.

Factors controlling the magnitude of these changes to the soil include fire intensity (heat), burning processes (combustion, pyrolysis), the magnitude, duration and depth of soil heating and the temperature thresholds at which different soil properties change. Some of these factors will be influenced by the soil itself, through the fuel available, its moisture content. Soil properties such as coarse fragment content, and antecedent mineral soil moisture levels.

Of the four key post-wildfire changes, loss of forest floor cover, changes in soil structure, and the development of an erodible ash layer are, in general, relatively obvious either visually, or by touch. The assessment of soil water repellency is more complex and requires some understanding of this soil characteristic. Soil water repellency is therefore discussed in more detail in the following section.

3.3 Soil water repellency (also termed hydrophobicity)

¹ Additional information is available at: <http://www.fs.fed.us/eng/rsac/baer/>

In some circumstances, excessive heating of soils can result in the formation of a water repellent layer (e.g. DeBano 1981; Doerr et al. 2000). Repellency can develop during fire through the volatilization of hydrophobic, organic compounds from litter or vegetation layers and their transfer into or within the mineral soil. Hydrophobic substances may also be derived from organic compounds already present within the soil. Fire can destroy repellency when the temperature is sufficient to destroy the organic compounds (generally taken to require temperatures in excess of 250°C and may require temperatures in excess of 500-600°C) (Doerr *et al.*, 2006). Although often associated with fire, soil water repellency also occurs on unburned terrain.

Through restricted infiltration and greater susceptibility to raindrop splash detachment, water repellent soils have the potential to enhance overland flow (or surface flow), preferential flow through the soil, and erosion. The spatial and temporal contiguity of repellency are acknowledged to be critical controls of the ability of repellency to enhance hydrogeomorphic responses (Shakesby *et al.* 2000).

Water repellent soils have a reduced attraction for water such that they resist wetting for a few seconds to weeks and more and water drops will bead on the soil surface (e.g. DeBano 1971; Doerr and Thomas 2000). Eventually, however, repellency will usually breakdown on prolonged contact with water, at which point the soil becomes wettable and infiltration can occur. Repellency is therefore a transient property, with soil moisture acknowledged to be a key variable in the breakdown and re-establishment of repellency. Some studies have reported a generally seasonal pattern where repellency is most extensive following prolonged dry weather but breaks down following wetter weather (e.g. Dekker and Ritsema 1994; Leighton-Boyce *et al.* 2005). However, the precise conditions and time scales over which repellency varies have yet to be determined and will likely vary considerably between different sites. The length of time that repellency persists through a rain event is critical to its ability to affect slope and catchment hydrogeomorphic responses and is one of the key questions being addressed in current research.

The spatial distribution of repellency in soils can also be variable, both in terms of the proportion or extent of the soil that may be repellent, and in terms of the degree of interspersed repellent and wettable soils. Spatial distribution patterns reported in the literature are diverse. They include contiguous surface repellency with discontinuous subsurface repellency, discontinuous surface repellency, wettable surface layers underlain by partially repellent soils, wettable layers underlain by a contiguous repellent layer and a decrease in repellency extent with depth (e.g. Barrett and Slaymaker, 1989; Leighton-Boyce *et al.* 2005; Ritsema and Dekker, 1998; Scott 1991, 2000).

The repellency that exists following a fire depends on many variables including fire temperature, fuel, burn duration, litter cover, antecedent soil moisture and antecedent repellency. Fire can create repellency, enhance or destroy repellency that is already present in the soil, and/or result in variable layers of wettable and repellent soils. One commonly reported layering effect found after fire comprises a wettable surface soil layer underlain by repellent soils of limited depth (thickness), which may or may not be horizontally contiguous. This layered effect is generally accepted to develop as a result of hydrophobic substances within the litter and topsoil being volatilized during fire and traveling down the temperature gradient into the soil and condensing onto soil particles at cooler depths. Any pre-fire repellency may be destroyed by high temperatures. Other fires, likely with lower temperatures or reduced heating times, have resulted in either continuous or partially repellent surface layers.

3.4 Potential hazards associated with water repellency

The presence of a water repellent layer in soil on a burned slope has the potential to:

- generate significant overland flow, because repellent soils have reduced infiltration rates;
- increase surface wash, as repellent soils are more susceptible to raindrop splash detachment; and
- increase preferential flow thorough wettable soil layers due to reduced moisture storage capacity within repellent soil layers

These factors can lead to:

- (i) enhanced hydrological response, i.e., increased direct runoff volume and decreased time of concentration, which can significantly increase stream flows and lead to flooding;
- (ii) increased rates and volumes of soil erosion, which may lead to bulking of the flow and triggering of debris flows/debris floods; and
- (iii) reduced soil moisture, which may negatively affect plant re-establishment.

The ability of repellency to enhance hydrological or geomorphic responses is linked to other factors that control catchment hydrogeomorphic response (e.g. Shakesby *et al.* 2000; Pierson *et al.* 2001; Doerr *et al.* 2006). Where the aim of post-fire risk assessment is prediction of the immediate hydrogeomorphic effects of fire on catchment response (e.g. flash flooding and erosion), assessments need to consider surface and subsurface soil hydrological properties, as well as vegetation and ground cover status.

Figure 1 outlines some of the conditions that control the impact of post-fire water repellency on slope and catchment hydrogeomorphic response. The figure emphasizes that there are many interacting factors that control post-fire catchment response, of which repellency is just one.

Forest floor (litter and duff) and vegetation

- The quantity, degree of decomposition and spatial contiguity of the post-wildfire forest floor influence its moisture storage capacity and its ability to protect against splash detachment and slope wash. Similarly, vegetation remaining after a fire is able to store moisture. A wettable ash layer may also have a considerable moisture storage capacity.

Repellent soils

- Three dimensional distribution and extent (surface or subsurface layers), the degree of interspersions of wettable and repellent soils (particularly in the surface layer), persistence following the onset of rainfall and location within the catchment will influence the ability of repellent soils to enhance hydrogeomorphic response.

Wettable soils

- Location (surface or subsurface), porosity and depth, antecedent moisture content, connectivity, hydraulic conductivity, erodibility of surface soils, and the occurrence of macropores will control the ability of wettable soils to counterbalance the effects of repellent soils, in particular through moisture storage.

Rainfall

- Intensity and duration of rainfall determine whether the moisture storage capacity of the forest floor and wettable soil layers is exceeded, and affect splash detachment and soil structural breakdown. The amount and distribution of rainfall will influence the rate at which repellency breaks down.

The above points emphasize that several factors, such as a remaining forest floor or sufficient wettable surface soil, may override the effect of repellency on catchment response.

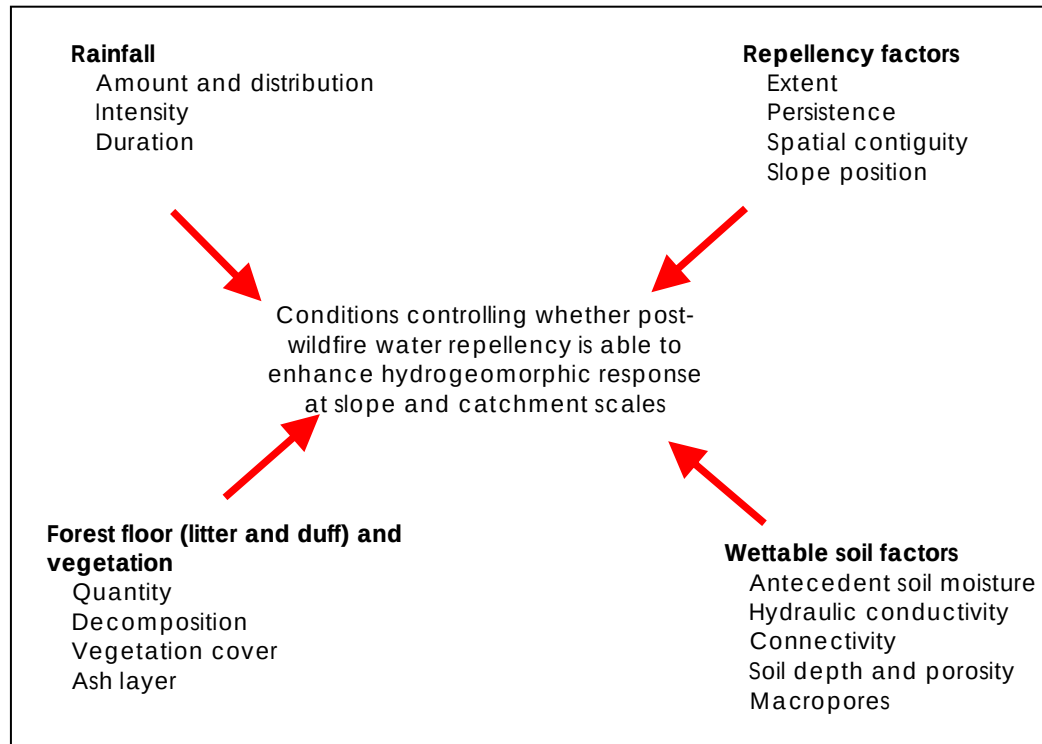


Figure 1. Conditions affecting water repellency.

3.5 Experiences from Previous Fires in the Southern Interior of British Columbia

To date there is only limited information on the occurrence, persistence or severity of repellency in British Columbia on unburned or burned terrain. This issue is the subject of a current UBC research project, for which only preliminary results are available at present. Water repellent soils were found in many areas burned in the 2003 fires, including areas that generated flooding during the fall 2003 and the summer of 2004. The persistence and spatial continuity of this repellency varied widely between different burn sites. During a systematic survey of burned sites during the summer of 2005, it was clear that water repellent soils were also present in adjacent unburned sites.

The photograph in Figure 2 was taken two months after the Okanagan Mountain Park fire (2003). The near surface soil profile shown is typical of those found in the high soil burn severity areas. It shows (i) pale colored ash on the soil surface (centre top) where heating was greatest (< 5 mm thick). The pale gray is ash, and the pale orange is a

mixture of mineral soil and ash that has experienced extreme heating. The second layer of blackened, charred soils beneath the pale ashy surface is between 10 and 20 mm thick. This blackened zone would have experienced lower temperatures because of the insulation provided by overlying soil, and lower oxygen levels than required for complete oxidation, resulting in partial, but not complete, destruction of organic matter at this depth. This layer is part of the mineral soil. These altered soil layers can be highly susceptible to erosion due to loss of structure and organic matter.

Below the charred zone, soils appear to have normal soil colour, the colour variation from pale (centre) to mid-brown indicating drier and slightly damp soil. It is these “normal-looking” soils that are typically water repellent after fire. Based on investigations to date, this layer is usually encountered somewhere between 5 and 25 mm below ground surface.

The charred soils and ash of the upper layers are typically highly wettable and erodible due to loss of organic matter and structure. During low intensity rain events they soak up water very readily. However, deeper percolation of water is impeded by the underlying water repellent soils.

In the photograph in Figure 3, the charred surface soil is glistening with water as it is saturated. Exposed soils beneath the black surface are pale and dry, and are very resistant to absorbing water from the overlying saturated soil. Note the water drop that has collected alongside the coin. Deeper into the profile, the soil is a darker brown and this is usually wettable soil that has little if any effects from the passage of the fire.



Figure 2: A profile through recently burned soil in Okanagan Mountain Park Fire, photographed within 2 months of the fire. Scale is provided by a hand trowel.

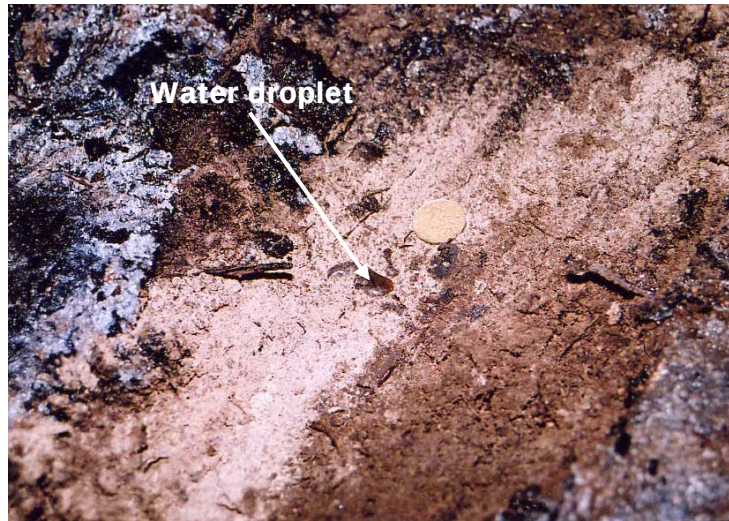


Figure 3: Profile of severely burned soil in Okanagan Mountain Park Fire (2003). Scale is provided by a dollar coin.

3.6 Assessing Soil Water Repellency

Any assessment of soil water repellency needs to address:

- where repellent soils are located within the area of concern (the extent and distribution), and,
- how long the repellency will persist through a rainfall event.

The repellency investigation should provide an understanding of repellency within the whole area of concern, even if only to confirm that repellency is only found under moderate and high soil burn severity areas. A more detailed repellency investigation can then focus on these areas in which repellency is present.

Techniques for assessing soil water repellency can be divided into two broad groups; those measuring the persistence of repellency when in contact with water, and those measuring the initial severity with which water is 'repelled'.

Persistence measurements include infiltrometers (e.g. Bond 1964; King 1981), rainfall simulations and the water drop penetration time test (WDPT) (Letey 1969). Severity measurements include the molarity of an ethanol drop test (MED) (also known as the critical surface tension (CST) test or % Ethanol test) (Letey 1969), the capillary rise method (Letey *et al.* 1962), the contact angle method (Letey 1969; Wessel 1988; Bachmann *et al.* 2000a,b) adsorption from an aqueous solution (Tschapek & Wasowski 1976), and the repellency index (Wallis *et al.* 1991).

For the purposes of the current risk assessment procedure, any tests must be suitable for field use, require limited equipment, and be suitable for making multiple measurements of repellency. Mini-disk infiltrometers, the WDPT test and the MED test meet these criteria.

The mini-disk infiltrometer (www.decagon.com) can be used to measure soil hydraulic conductivity. Its use in field assessments of soil burn severity is described in Lewis *et al.* (2005).

The WDPT and MED tests are described in detail in Letey (1969). The Water Drop Penetration Time (WDPT) test involves the application of drops of distilled water to the soil surface and noting the time taken for infiltration to occur. It is based on the gradual breakdown of repellency when in contact with water and gives an indication of the persistence of repellency. In general, 5 drops are applied to the soil and the time at which the third droplet infiltrates (i.e. the median WDPT) is recorded (Doerr 1998). The WDPT can range from instant infiltration to in excess of several hours. Infiltration times are usually grouped into arbitrary descriptive classes. There are several different classifications of both the threshold between wettable and repellent soils and of the time intervals between the different classes, for which there is no agreement within the literature. For example, the threshold between repellent and wettable soils has been placed at 1 second (s) (Roberts and Carbon 1971; Ma'shum and Farmer 1985), 3 s (Crockford *et al* 1991), 5 s (Krammes and DeBano 1965) and up to 60 s (DeBano and Krammes 1966; McGhie and Posner 1981). Similarly, a range of different arbitrary infiltration time classes has been used, as shown in Table 2.

	Adams <i>et al.</i> (1969)	Bisdorn <i>et al.</i> (1993)	Roberts & Carbon (1971)
Wettable	< 10	< 5	< 1
Slightly repellent	10 – 60	5 - 60	1 – 10
Moderately repellent	-	60 – 600	10 – 60
Severely repellent	> 60	600 – 3600	>60
Extremely repellent	-	> 3600	-

Note: WDPT classifications used by different authors to distinguish between different repellency classes. WDPTs are shown in seconds.

Table 2. Water Drop Penetration Test infiltration time classes.

The MED test indicates how strongly water is repelled on initial contact with the soil (i.e. the initial severity of repellency). It gives an estimate of the surface tension and hence repellency of a soil, based on the known surface tensions of a range of solutions of ethanol in distilled water. Drops of these solutions are applied to the soil and their infiltration behaviour over a given number of seconds is observed. If the surface tension of the droplet is higher than that of the soil, it will remain on the soil surface, whereas if the droplet surface tension is lower than that of the soil, it will infiltrate instantly. The concentrations used and the observation time vary slightly between studies. For example, the methodology of Crockford *et al.* (1991) involved the application of sets of 5 droplets of ethanol solution to the soil, the concentration of each set increasing until at least 3 of the 5 droplets infiltrate within 3 seconds. The lowest concentration at which 3 or more droplets infiltrate was recorded as the test result. The ethanol concentrations used within this study were 0, 1, 2, 3, 5, 8.5, 13, 18, 24, 36, 50 % ethanol by volume. This is comparable with Doerr *et al.* (1998) who used seven of these concentrations (0, 3, 5, 8.5, 13, 24, 36 % Ethanol).

Both the MED and the WDPT test can be conducted under field or laboratory conditions. Whilst there are no established rules for the tests, there are several guiding principles should be that should be taken into consideration. Since surface roughness and pore geometry can affect infiltration, (Wessel 1988), the soil surface should be smoothed by hand prior to drop application. Drop sizes should be kept constant by the use of a standard dropper bottle and applied to the soil from a very low height as the kinetic energy of a drop applied from a height may increase the surface energy of the water

drop and thus decrease its surface tension in comparison to a stationary drop. Increases in water temperature and solute content also reduce the surface tension of the water (Chen and Schnitzer 1978; King 1981), so that water should ideally be deionised and at a constant temperature. However, distilled water is more commonly used and room or field temperatures are considered acceptable (Wallis and Horne 1992). For the purpose of this procedure, focus is placed on using the same solution, even stream water, throughout the investigation to ensure comparability.

For investigations concerning the effect of repellency on watershed hydrogeomorphic response, the WDPT measure of persistence is more appropriate than the measure of initial severity provided by the MED test. However, as the WDPT test involves assessment of the time taken for drops of distilled water to infiltrate into a soil sample, it can be extremely time consuming if repellency is particularly persistent. The more rapid MED test has been used as a surrogate for the WDPT in studies where a good correlation has been found between the MED and WDPT test results (e.g. Crockford *et al.* 1991; Doerr 1998; Harper and Gilkes 1994). In contrast to these Portuguese and Australian studies, Dekker and Ritsema (1994), in a study with some 5000 samples of Dutch sands, found only limited correlation between the results from the two methods, although the correlation was somewhat stronger at higher than at lower levels of repellency. These varying results suggest that any relationship between the % Ethanol and WDPT tests may be site and/or soil specific.

Selecting the appropriate test will depend on the resources available and the time frame required for test results. All three measures have advantages and disadvantages. In combination, the WDPT test can be used to assess the presence or absence of repellency, its distribution and, if extended time tests are used, its persistence. Alternatively, the % Ethanol can be used to assess distribution and severity (as a surrogate for persistence) if a good relationship with WDPT test is identified. These results can be combined with use of the mini-disk infiltrometer to assess hydraulic conductivity on wettable soils.

The equipment required to complete these tests includes a trowel, tape measure, dropper bottles containing pure water and pre-made ethanol and distilled water solutions, and a mini-disk infiltrometer and water supply.

4.0 HYDROLOGIC ASSESSMENT: HAVE RAINFALL OR SNOWMELT GENERATED PEAK FLOWS INCREASED AS A RESULT OF THE FIRE?

The focus of the hydrologic assessment is the change in magnitude of the rainfall and snowmelt generated peak flows resulting from the loss of canopy interception and, for the short-term, reduced infiltration (due to water repellency, and loss of vegetative cover and forest floor).

The assessment is focused on the increased probability of occurrence following wildfire of:

- increased storm peak flows as a result of a more rapid response to rainfall;
- increased spring freshet peak flows; and
- increased total flow volume.

Although there are a variety of models that have been developed that can be used to estimate pre-fire and post-fire peak flows, none are considered operationally effective at this time. Until such time as quantitative results are available, it will be necessary to make

qualitative assessments of the potential for peak flow increases and whether the increases are “significant” or not.

The hydrologic assessment is one component of the post-wildfire risk assessment, and as such if the work is being carried out by a team, the hydrologist needs to include the results of other components of the study, and use them as part of the input to the hydrologic hazard assessment. These include the results of the vegetation burn severity, and soil and forest floor burn severity, assessments.

The following sections provide additional details for consideration while undertaking the hydrologic assessment as well as details on selected peak flow models.

4.1 Short-term Changes (approximately 0-3 years)

A significant increase in the peak flow magnitude can occur on slopes burned to a moderate to high severity by short duration–high intensity rainfall, that can lead to the triggering of hazardous events. The increase in the magnitude of the peak flows can be determined by calculating the difference in runoff between the “design” rainstorm for pre-wildfire and post-wildfire conditions.

Increased storm peak flows and more rapid response to rainfall result from the changes in soil and vegetation cover. Peak flows in the streams and non-channelized hollows within and downslope from the burned slopes can be substantially increased by rapid surface runoff, as the lag time (i.e. the time of concentration) is reduced from the time the rainfall arrives at the ground surface to the time it is delivered to the channel (when compared to the pre-wildfire conditions). Spittler (1995) notes that the generation of this significant runoff reduces the size of storms necessary to mobilize the stored sediment in the non-channelized hollows and streams, increasing the likelihood of occurrence of a slope hazard. It has been reported in the United States that post-wildfire peak flows resulting from rainstorms can be as much as three orders of magnitude greater than those for pre-wildfire conditions (Neary *et al.*, 2005). Over the longer term higher peak flows, earlier runoff and increased water yields can persist for years until the forest cover and canopy closure are restored to near natural conditions.

To understand how the hydrologic response in a watershed might be affected by a wildfire, it is necessary to understand the local climate that generates the runoff. Short-term storm flow responses (i.e. rainfall generated) are defined on the basis of the extent of the burned area and the burn severity (Parsons, 2003). For the storm generated peak flows, recent work in the US suggests that the peak flows resulting from the 2, 10 and 25-year 1-hour rainstorm provide the best data required to analyze the peak flow hazard (Cannon *et al.*, 2004). Unfortunately the availability of rainfall frequency data is limited for most of the SIFR. This is a significant gap in the critical data required for the hydrologic analysis.

In the absence of local intensity/duration/frequency curves it will be necessary to use precipitation data from other sources that may be available within a reasonable proximity to the fire. It has been suggested that a request be made to Ministry of Forests and Range climatologists familiar with the climate data for the SIFR, to recommend appropriate design rainstorms for the various hydrologic zones.

The burned watersheds in the Okanagan Mountain Park Fire (2003) provide examples of some of these fire enhanced hydrological responses to rainfall. In the watersheds investigated, areas with high burn severity included up to 100% of some catchments. It was determined that water repellent soils were extensive on slopes. In the short-term, the

impacts to soil conditions reduced infiltration rates and increased the magnitude of the peak flows that could be generated by rainfall events. This was confirmed following a short duration–high intensity rainstorm in October 2003 over the Lebanon Creek watershed that resulted in peak flows ranging from 20-30 times those that existed pre-fire (Dobson and Smith, 2003).

The following models might be considered when calculating the rainfall generated peak flows:

- DHSVM – Distributed Hydrology Soil Vegetation Model (developed at the University of Washington)
- SWMM - Storm Water Management Model (developed by the US Environmental Protection Agency);
- HEC-HMS – Hydrologic Engineering Center - Hydrologic Modeling System (developed by the US Army Corps of Engineers)
- FS WEPP – Water Erosion Prediction Project (developed by US Department of Agriculture Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, Moscow, Idaho).

The intent of the modeling is to compare the pre-fire and post-fire storm generated peak flows in order to determine the change in hazard.

Unfortunately none of the models are considered to be feasible to determine peak flows in the short timeframe required for a rapid risk assessment following a wildfire at this time. After further research and calibration they could be a valuable asset. The WEPP model is used extensively by agencies in the US to determine post-wildfire peak flows since there has been an extensive investment in calibration work over the past twenty years. Additional information on these models is provided in Appendix 3.

4.2 Long-term Changes (approximately 3-30 years)

Over the long-term, the impacts of wildfire may include an increase in snowmelt generated peak flows (as a result of elevated snow accumulations) and decreased evapotranspiration rates that can lead to an increase in the groundwater levels in the surficial materials present. It has been estimated that snowmelt dominated post-wildfire peak flows could be increased as much as 40% over the pre-wildfire levels (Schnorbus and Alila, 2004). These impacts can persist for decades until the canopy closure is restored (generally estimated to be more than 30 years).

Wildfire impacts can also change the time at which the freshet peak flows occur (similar to clear-cut harvesting). Peak flows in southern interior watersheds typically generated from snowmelt could have the timing of the peak advanced by as much as two weeks depending upon the location and extent of the burned area. Research by Cheng (1998), Potts (1984) and Bethlahmy (1975) into the effects of the loss of forest canopy to the mountain pine beetle indicates that peak flows may be advanced from 2 to 21 days. It is likely that if there has been extensive loss of canopy in the higher elevations where snow accumulates, that there would be similar advances in peak runoff.

The impact of the advancement in the timing could be to synchronize the higher elevation runoff with the lower elevation runoff resulting in even larger, potentially destructive peak flows.

The DHSVM has been used to estimate the impacts on runoff for varying reductions in the amount of forest cover, including 100% clear-cut (Schnorbus *et al.*, 2004). The worst-case

scenario modeled was a 100% clear-cut (that would be similar to 100% of the snow accumulation zone being burned to a high severity). Results suggested that the snowmelt generated peak flow would be increased by 40%. This model was applied to the Okanagan Mountain Park fire to calculate the post-fire impacts on peak flows. The design flood used was the 200-year peak flow (the standard used in BC in the Flood Hazard Program).

Fortunately for the long-term analysis, data are readily available from hydrometric stations and snow courses throughout the region. This data is required to assess the long-term snowmelt generated peak flows. Long-term hydrologic responses are a function of the location, extent and burn severity of the fire in the snow zone and the post-fire hydrologic recovery.

5.0 HAZARDOUS EVENT ASSESSMENT: WHAT IS THE LIKELIHOOD OF A HAZARDOUS EVENT BEING TRIGGERED BY A RAINFALL GENERATED PEAK FLOW WITHIN AND/OR DOWNSLOPE FROM THE BURNED AREA?

Wilford et al (2004) has noted that central to hazard recognition in land-use planning is the need to identify the specific natural hazard processes within watersheds and/or sub-basins. Alluvial and colluvial fans at the mouths of catchments are formed by and can be subject to floods, debris floods and debris flows (hydrogeomorphic processes) with a potential for resulting damage to infrastructure and loss of life (VanDine 1985). An understanding of the hydrogeomorphic characteristics of burned or partially burned watersheds/sub-basins is essential in understanding and managing the response of these slopes to intense climatic events.

The hazardous events that can be triggered by significant hydrologic responses within a burned watershed include landslides, debris flows, debris floods and flooding. Hungr et al (2001) describes debris flow as a very rapid to extremely rapid flow of saturated, non-plastic debris in a steep, confined or established stream channel. The surging behaviour and development of coarse surge fronts can cause debris flows to have peak discharges 5 to 40 times greater than floods (Van Dine 1985, Hungr 2000). Debris flows can be one of the most hazardous consequences of rainfall on burned hillslopes and they pose a significant risk distinct from other sediment-laden flows due to their unique destructive powers (Cannon et al 2004). Numerous burned watersheds within the southwestern US have generated post-fire debris flows following intense rainfall events that have impacted public safety, private property and infrastructure.

Significant debris flows were triggered in stream channels on and downslope from the burned slopes in the Kuskanook Creek and Ingersol fires in BC following the 2003 wildfire season, and following the 2004 Botanie fire. The Kuskanook Creek debris flow destroyed two buildings, (which were unoccupied at the time), while the Botanie debris flow derailed a stationary train on the CN line.

A debris flood is described as a very rapid, surging flow of water that is heavily charged with debris in a confined channel (Hungr et al 2001). Hungr (2000) notes that a debris flood may transport quantities of sediment similar to a debris flow in the form of massive surges propelled by the tractive forces of water overlying the debris. The relative peak discharge of debris floods can be up to twice those of flood discharges and can continue to move in channels with considerably flatter gradients than those required for debris flows (Hungr et al 2001). Debris flows can be diluted downstream and assume the characteristics of a debris flood.

The alluvial/colluvial fans created by these hazardous events have unique depositional and gradational characteristics (Wilford et al 2004) and it is important to identify the hydrogeomorphic responses of burned catchments in order to accurately assess the risk and develop mitigative measures, where required.

Debris floods and flooding were triggered in several of the burned watersheds from the 2003 wildfire season in BC following intense rainfall events (e.g. the Cedar Hills fire, the Okanagan Mountain Park fire, the Strawberry Hills fire and the Lamb Creek fire). These hazards, while not as destructive, presented a significant risk to road structures (both urban and logging), and to highway users and the adjacent infrastructure. Substantial upgrading of the drainage structures costing several million dollars was required on many of the stream crossings within City of Kelowna limits following the Okanagan Mountain Park fire.

In determining the likelihood that a hazardous event (i.e. a debris flow or debris flood) will be triggered by the rainfall generated peak flow, two mechanisms for initiation should be reviewed. These are: -

1. The Sediment Bulking mechanism (sometimes referred to as the instream triggered debris flow/debris flood); and
2. The Landslide Triggered mechanism (as a result of an infiltration induced landslide that originates from the sidewalls, headwalls or adjacent unstable slopes).

5.1 Sediment “Bulked” Debris Flow/Debris Flood Events.

Cannon et al (2004) notes that debris flows/floods can be initiated by sediment bulking of surface and channelized flows that is generated by runoff from high intensity rainfall events within burned watersheds. The flow concentrates in depressions, non-channelized hollows and streams within and downslope from burned watersheds and basins. The density of the flow is increased (i.e. “bulked”) by the sediment eroded from the surface (i.e. the burned organic layer and the powder-like, upper soil layer) along with the sediment stored in these features. The energy developed in the bulked flood flow scours the hillslopes and channel margins, destroy instream structures, greatly increase the volume of channel flow, and mobilize channel bed load. This can lead to the initiation of debris floods and/or debris flows depending on the watershed and channel characteristics.

In a study of the hydrological and sedimentologic response of 2 burned watersheds in Colorado completed by Martin and Moody (2001), sediment erosion was not spread evenly among the channels within the watershed. 7 to 9 percent of the eroded sediment came from first-order channels, 16 to 22 percent came from second-order channels and the majority (about 70 percent) of the eroded sediment came from third-and fourth-order channels.

A “Rule of Thumb” for erosion estimation following a wildfire (developed by Martin and Moody (2001) suggest a 20% increase on the hillslopes and an 80% increase in the stream channels and non-channelized channels. McDonald and Stednick 2003 noted that erosion could be increased by up to 100% relative to unburned areas.

Several catastrophic debris floods and debris flows were triggered within and downslope from the burned watersheds in BC following the 2003 wildfire season after short duration high intensity rainfall events. Moderate to deep erosion (i.e. 0.3 to 2 m) of the stream

channels and non-channelized hollows was characteristic of these watersheds. In addition, the burned organic layer and the powder-like, upper soil layer (that generally varied from 5 to 10 cm thick) was washed from the burned slopes by these rainfall events and was deposited as thin veneer a considerable distance downslope. It is possible that debris flows or debris floods in several examples (two in the Kuskonook fire and one in the Lamb Creek fire) were caused by a large flow of water entraining sediment by eroding deeply into the stream channel or undercutting the banks, rather than by the “sediment bulking” mechanism (Jordan et al, 2004).

[[many references are not in the reference list]]

5.2 Infiltration Induced Landslide and Debris Flow/Debris Flood Events.

Cannon et al (2004) suggests that infiltration induced landslides that trigger debris flows/debris floods in burned watersheds most frequently occur in response to prolonged periods of rainfall or a prolonged rainfall in combination with rapid snowmelt or “rain on snow” event. It is important to note that these slopes failures can occur on slopes that are marginally stable regardless of whether they were impacted by a wildfire.

The occurrence of infiltration induced landslides within burned watersheds can occur both in the short term (i.e. 0 to 3 years) and over the long term (i.e. 3 to 20 years) as the slopes re-vegetate naturally. Spittler (1995) notes that infiltration induced are less likely in the short term following a wildfire due to the increase in surface runoff and reduced infiltration). In the long term however, the surficial materials present on the burned slopes can be affected by rapid hydrologic events that can cause increases in the soil pore water pressures and total stresses, increasing the likelihood of a slope failure on moderately steep to steep slopes (generally steeper than 50% in southern BC).

Infiltration induced landslides are generally shallow, translational slope failures (less than 2 m thick) that originate in the upper layer of weathered surficial material that mantle the till, colluvial and glaciofluvial slopes in southern BC. Slope failure in these materials occurs when the shear stresses (the driving force) equals or exceeds the shear strength (the resisting force). Cannon et al (2004) note that the shear strength can be comprised of the combined resistance to movement provided by friction on the shear surface, the soil cohesion and the reinforcing provided by the tree and plant roots (also known as the composite shear strength). The shear forces are imparted by the mass of the soil (and the trees), the soil pore water pressure and gravity. The balance between the driving and the resisting forces depends on several factors including the slope steepness, the thickness and drainage characteristics of the upper surficial layer and the pore water pressure (related to the soil moisture content).

An increase in the soil moisture should be expected on burned slopes due to the reduction in interception of precipitation and the decrease in evapotranspiration following the loss of tree cover. This can lead to the development of elevated groundwater levels and pore water pressures in the surficial materials, increasing the driving forces for slope failure. These rates will return to pre-fire levels as canopy closure and hydrologic recovery begins to occur (generally at the 20 year period, however this is dependant on the biogeoclimatic zone and geographic location in BC).

As the roots on the burned trees killed by the wildfire deteriorate, a reduction in the composite soil shear strength (i.e. the soil shear strength and the reinforcing provided by the roots) can occur. This can lead to a reduction in the forces resisting slope failure particularly during periods of elevated groundwater levels. The reinforcing effect is restored over time as the new root growth begins to dominate. An overlap exists when

the loss of root strength due to the dead trees is greater than the reinforcing provided by the new roots. Cannon et al (2004) notes that there is a significant body of knowledge on the root decay rates and the effect on slope stability following logging however little work has been done on this effect following a wildfire.

The tree mortality on slopes that are burned to a moderate to high severity is generally extensive. This mortality can produce similar hydrologic effects (both surface and sub-surface) to slopes that have been logged.

If the runout from a landslide exceeds a threshold magnitude, and is delivered to the channel of a gullied stream during a peak flow event, a debris flow/debris flood can be triggered. If a debris flow/debris flood is not triggered, the runout can be stored in the stream channel as bedload that can be mobilised during extreme peak flow events.

6.0 RISK ANALYSIS

The initiation of the post-wildfire risk assessment procedure follows the recognition that some level of hazard and risk exists that may need to be managed. According to the proposed SOP, this procedure will assess the risk to the following elements:

1. Public Safety; this includes people occupying structures and buildings, users of infrastructure such as highways and train lines and drinking water quality.
2. Infrastructure, such as hydro and telephone/cable lines, roads and highways, gas and oil pipelines and rail lines.
3. Buildings including commercial and residential structures.
4. Water quantity and quality for domestic and industrial users.

The outcome of this procedure is not to determine if the risk to these elements is acceptable, it is to present the level of risk so that it can be communicated to the appropriate decision makers to assess whether mitigative measures should be undertaken.

The basic underpinning of this procedure is presented in Land Management Handbook 56, *Landslide Risk Case Studies in Forest Development Planning and Operations* (Wise, Moore and VanDine, 2004).

Figure 4, adapted from Land Management Handbook 56, shows the steps in the decision-making framework for risk analysis. After each step, a decision must be made: go forward to the next step, go backward to the previous step, or take action. The process is iterative, and it is not unusual in slope hazard risk management projects for a stakeholder to revisit previous steps. The analysis presented in this procedure stops at the completion of Step 3, Risk Estimation. The information gathered up to this point is then conveyed to the appropriate decision makers to determine whether further risk evaluation and mitigation is required.

It is important in risk analysis and management to initiate communication with stakeholders early on in the process, particularly if there is a significant risk to public safety. The risk estimates should be communicated in clear and direct terms to the affected stakeholders and presented in a manner that allows for simple comparison with established thresholds of acceptable or tolerable risk.

The analysis of the risk associated with the post-wildfire hazardous discussed in this procedure involves estimating the probability of the event occurring and the consequence of such an occurrence. The probability of occurrence (qualitatively referred to as likelihood) is an estimate of the chance of the event occurring.

Consequence is the effect, or expected effect, of the hazard on a specific element. That is, if the event occurs will it reach the site that the element is occupying (i.e. the spatial effect) and if it does, is the site occupied by the element (i.e. the temporal effect) and if it is occupied, what is the exposure of the element to the hazard (i.e. the vulnerability).

For the purpose of this procedure, it is suggested that the risk analysis be completed up to the stage of determining whether there will be a spatial interaction with the element at risk only (also known as a partial risk analysis).

This is due to:

- (i) The level of uncertainty associated with assessing the probability of the hazard occurring; and
- (ii) The possibility that the fire could be extinguished (or brought under control) by a rainstorm that triggers the hazardous event. Time is of the essence in completing the assessment.

Partial Risk, $P(HA)$, is described in Land Management Handbook 56 as the product of the probability of occurrence of a specific hazardous landslide (or in this case a hydrologic or slope hazard) and the probability of the event reaching or otherwise affecting the site occupied by a specific element.

The partial risk is then mathematically expressed as:

$$P(HA) = P(H) \times P(S:H)$$

Partial risk does not consider the vulnerability of the element, and therefore is not a complete estimate of risk. In practice, partial risk is usually the preferred type of analysis when little is known about the vulnerability of the element or where an estimate of vulnerability is not required.

Quantitatively, partial risk is expressed as the probability (between 0 and 1) of a hazard occurring over a specified time period, either annual or long term, corresponding to $P(H)$. Quantitative landslide risk analysis methods use numerical values, or ranges of numerical values, of probabilities to estimate the risk.

The risk analysis may be carried out using quantitative or qualitative methods, depending on the type and scope of the analysis. If quantitative methods are used it is recommended that the results be rounded to 1 decimal point as more than one, may imply a greater degree of accuracy than is available.

Qualitatively, risk may be expressed using ratings such as *very high*, *high*, *moderate*, *low*, and *very low likelihood* of a specific hazard over a specified time period. There are no standard definitions for qualitative ratings of probability of occurrence, vulnerability, and worth; therefore, to avoid ambiguity, they must be defined as part of the risk analysis.

Further analysis of the temporal effects and the exposure/vulnerability should be completed if risk mitigation measures are proposed. This is considered beyond the scope of this procedure.

After assessing the probability of occurrence of a hazardous event within and downslope from the burned areas, the risk to the identified elements should be analyzed. As in geotechnical applications for landslide analysis, it is recommended that event trees or risk matrices be used.

Event trees are a relatively simple and thorough method of decomposing the risk components. This method is usually associated with quantitative risk analysis, but can provide a helpful framework for qualitative risk analysis, particularly for more complex projects.

For a more complex analysis, the components can be subdivided, and more than two possible outcomes can be used to estimate any type of probability. The estimates can be either objective or subjective (as is usually the case with slope hazards). The specific risks and specific value of risks located on the right side of each branch are calculated by multiplying probabilities and values along the branch (refer to Section 3.7.3 in Landslide Management Handbook 56 for a more detailed discussion on this).

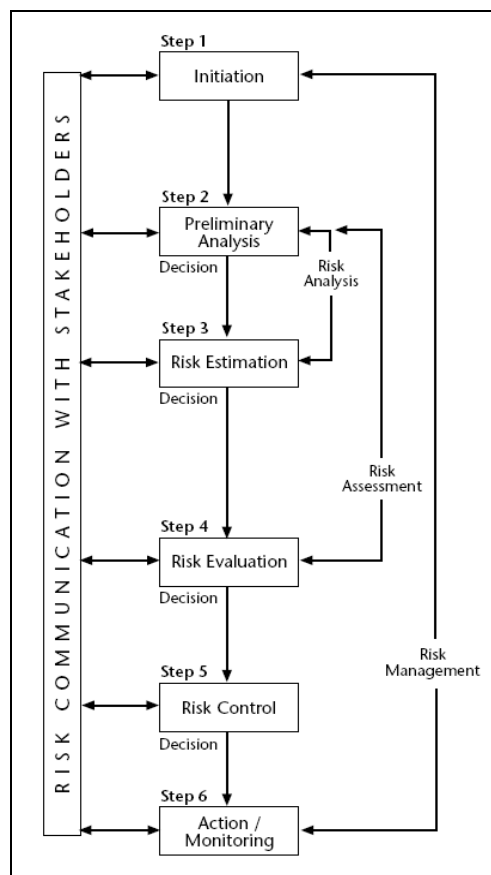


Figure 4: Six steps in the decision-making framework for risk management (adapted from Land Management Handbook 56).

Event trees encourage the analysis of many, if not all, of the appropriate components. The sum of the outcomes of each component numerically adds up to 1. During the analysis, if relative qualitative ratings are more appropriate than numbers, ratings can be used, but the event tree then becomes qualitative.

Risk matrices are used to combine two risk components and this method is usually associated with qualitative risk analysis. The risk components are in the lower left and upper right portions of the matrix. The resulting combination of the components is described in the upper left portion of the matrix, and defined in the lower right portion of the matrix (refer to Section 3.7.3 in Landslide Management Handbook 56 for a more detailed discussion on this). Criteria for the two sets of component ratings, and the resultant risk rating, must be defined.

Insufficient research has been completed on the wildfires in BC that have been affected by significant climatic events that triggered hazardous events to say with certainty what the likelihood of occurrence is (i.e. due to the lack of site specific rainfall data at the time of initiation) and whether there are any common themes with regards to site characteristics that need to be present for these events to occur. As this data is collected and compiled, a review of this procedure should be completed to determine whether additional analysis of the temporal effects and the exposure/vulnerability should be incorporated.

7.0 FIRES IN THE SOUTHERN INTERIOR OF BC AND WESTERN UNITED STATES WITH MASS WASTING AND FLOOD EVENTS

Table 3 provides a summary of the characteristics of a variety of fires that have occurred with the SIFR since 1973 where post-wildfire slope hazards have occurred. The amount of detail varies between fires since there was no specific format for undertaking the reviews. The specifics for each fire were extracted from reports prepared by staff from the SIFR or from consultant's reports.

Table 4 provides a similar summary for selected wildfires within the western United States as extracted from work undertaken by Susan Cannon and other reports where available from the US Forest Service.

Table 3. Summary of Wildfire Characteristics for Fires within the SIFR from 1973 - 2005

Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
Eden Fire, 1973.	Not available (N/A).	N/A.	N/A.	N/A.	Debris flow/debris avalanche (1975); 2 debris flows/debris avalanches (1976); debris avalanches (1982/1983).	Generally N/A; "rain on snow" event may have triggered 1976 hazards.	Private property and residences.
Tiffen Fire, 1984.	1500 ha.	N/A	N/A	N/A	Rainfall extinguished fire, eroded soil and mobilized debris flow.	N/A	Forestry Road, railway, highway.
Silver Fire, 1998.	5300 ha.	N/A	N/A	N/A	Gully erosion (1999); 15 debris slides (2000 to 2002).	Private property and residences	N/A

Table 3 cont'd. Summary of Wildfire Characteristics for Fires within the SIFR from 1973 - 2005

Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
Okanagan Mountain Park Fire, 2003.	28,000 ha.	N/A	N/A	N/A	Debris floods and flooding (2003).	10 to 20 mm in a 20 to 45 minute period; 1:10 to 1:100 year return period events.	Infrastructure, residences, forestry roads, public safety, drinking water quality.
Cedar Hill Fire, 2003.	3500 ha.	N/A	N/A	N/A	Debris floods, flooding and debris flows.	50 to 60 mm in 1 hour; 1:20 to 1:25 year return period event.	Highway 97, residences and private property.
Strawberry Hills Fire, 2003.	5700 ha.	N/A	N/A	N/A	Flooding and debris floods (2004/2005).	N/A	Private property and Highway 5.
Hellroar Fire, 2003.	N/A	N/A	N/A	N/A	Debris slide (date unknown).	N/A	Forestry Road.
Mt Beaven Fire, 2003.	N/A	N/A	N/A	N/A	Debris flows (2004).	N/A	Forestry Roads.
Kuskanook Fire (including Jansen Creek and un-named stream), 2003.	990 ha.	Kuskanook Creek 44%, Jansen Creek 29% & un-named stream 21%.	Kuskanook Creek 560 to 2130 m, Jansen Creek 560 to 2120 m & un-named stream 560 to 1700 m.	Kuskanook Creek 0.7, Jansen Creek 0.83 & un-named stream 0.98.	2 debris flows (2004).	4 to 8 mm, although 36 mm in the days leading up to the event.	Residences, Highway 3A/access road and public safety.

Table 3 cont'd. Summary of Wildfire Characteristics for Fires within the SIFR from 1973 - 2005

Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
Vaseux Fire, 2003.	N/A	N/A	N/A	N/A	Flooding and debris floods.	9 to 12 mm in 45 minutes, return period not known.	Highway 97, private property, forestry roads.
Lamb Creek Fire, 2003.	11,000 ha.	N/A	N/A	N/A	Debris flood.	N/A	Forestry roads.
McGillivray Fire, 2003.	11,000 ha.	N/A	N/A	N/A	Erosion event (2004), debris flow (2005).	N/A	Water supply.
McClure Fire 2003.	26,000 ha.	N/A	N/A	N/A	Debris flow (2004), flooding (2005), small debris slides (2005).	N/A for 2004, "rain on snow" event 2005.	Access road & private property.
Botanie Fire, 2004.	N/A	N/A	N/A	N/A	Debris flow (2005).	14.5 mm in 1 hour.	Derailed stationary train on CN line.
Sleetsis Fire (including un-named sub-basins A and B), 2005.	4342 ha.	Sleetsis Creek 25%, un-named A 30% and un-named B 45%.	Sleetsis Creek 260 to 1800 m, un-named A 240 to 1790 m & un-named B 340 to 1390 m.	Sleetsis Creek 0.28, un-named A 0.45 and un-named B 0.71.	Minor debris flow (2005).	N/A	N/A

Table 3 cont'd. Summary of Wildfire Characteristics for Fires within the SIFR from 1973 - 2005

Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
Ingersol Fire, 2003.	N/A	N/A	N/A	N/A	Several debris flows and debris slides.	The highest intensity rainfall from any of the stations was 5.3mm/hr. The highest 24 hr rainfall was 37.2mm, the highest 2 day rainfall was 52mm and the highest 7 day rainfall was 68mm.	Forestry roads.

Table 4. Summary of Wildfire Characteristics for Wildfires in the Western United States¹							
Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
Myrtle Creek Fire, Idaho, 2003.	3600 Acres	N/A	N/A	N/A	Raveling of burned ash layer.	N/A	City of Bonners Ferry drinking water.
Simi Fire, California, 2003.	107,599 Acres	Happy Canyon Watershed 70%; Tapo Canyon 50%; White Oak 40%; Devils Canyon 50%; Chivo 70%; North Simi Dry Canyon 50%;	N/A	N/A	N/A	N/A	Happy Canyon: - recreational park, utility access, flood control structures for a residential area & golf course; Tapo Canyon: -oil fields, mining, golf course, residential area; White Oak: - recreational park, highway drainage structures & flood control structures; Devils Canyon: - roads; Chivo: -golf course; North Simi Dry Canyon: - residential area & hospital;

1. Refer to the following site for additional information on any of these fires plus ~600 other fires where there have been erosive responses in the western United States - <http://pubs.usgs.gov/of/2005/1218/Report.html>.

Table 4 cont'd. Summary of Wildfire Characteristics for Wildfires in the Western United States

Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
Verdale Fire, California, 2003.	8,488 Acres	Del Valle Canyon 15%;	N/A	N/A	N/A	N/A	Del Valle Canyon: -park facilities and parking lot;
Buffalo Creek Fire, Colorado, 1996.	11,900 acres	N/A	N/A	N/A, however relief ratio is 0.05	300,000 cubic yards of sediment was eroded and triggered a debris flood.	5 inches of rainfall fell in 1 hour on July 12 th 1996	2 people killed; water quality in Strontia Springs Reservoir (City of Denver's water supply) and 4 homes destroyed
Oster Lake Fire Idaho, 2001.	530 Acres.	0%	2900 to 3100 feet.	N/A	None	None	Water quality for fish hatcheries
Dome Fire, New Mexico, 1996.	6684 ha	Capulin Creek 36%; North Tributary 22%; South Tributary 2%.	Capulin Creek 1024m; North Tributary 735 m; South Tributary 575 m.	Capulin Creek 0.16; North Tributary 0.3; South Tributary 0.26	1 Debris flow in the North Tributary (1996); severe flooding in Capulin Creek (1996); no response in the South Tributary.	N/A	Cabin.

Table 4 cont'd. Summary of Wildfire Characteristics for Wildfires in the Western United States

Wildfire and Year	Burned Area	% Burned to Moderate to High Severity	Relief	Melton Ratio	Hazardous Event and Year	Rainfall and Return Period Estimate	Element(s) at Risk
South Canyon Fire (Storm King Mountain) Colorado 1994	2000 acres.	N/A, however 5 sub-basins were greater than 80% burned.	N/A	N/A, however the average watershed gradient is 30% with some slopes as steep as 70%.	Several debris flows.	N/A	4 lanes of I-70.
Cerro Grande Fire, New Mexico	48,000 acres.	14 sub-basins burned	N/A	Ranges from 0.63 to 0.98 in the sub-basins were debris flows were triggered.	5 debris flows were triggered in 2002.	Varied from 2 to 14 mm.	Residences and private property.
Yellowstone Fire, Wyoming	1.4 million acres.	N/A for 12 km Sub-basin, however more than 90% of the sub-basin was burned.	N/A	N/A, however relief ratio is 0.38.	1 debris flow.	N/A	N/A

8.0 POST-WILDFIRE EXPERIENCES OF SOUTHERN INTERIOR FOREST REGION STAFF

Prior to 2003, the assessment of post-wildfire hazards was limited to a few site-specific instances, and was not applied on a broad scale throughout the region. In 1998 staff from the Kamloops Forest Region (now part of the SIFR) completed a detailed assessment of the Silver Creek fire near Salmon Arm. The two reports prepared were *The Silver Creek Fire Watershed Hazards Assessment* and the *Technical Supplement to "The Silver Creek Fire Watershed Hazards Assessment Report"*. Prior to the Silver Creek fire, MOF staff had completed site assessments only after an erosion event. The Silver Creek approach was based on the best professional knowledge at the time. What was lacking was a method for systematic assessment of water repellency, although a few assessments of that property were completed (G. Hope, pers. comm.). This approach was used mainly due to a lack of experience in assessing the potential hazards after wildfires).

Following the 2003 wildfires, overview risk assessments were carried out by MOF staff for the purpose of identifying fires that presented a risk to downslope values. Further work was conducted on the Cedar Hills, Strawberry Hill, McLure, Kuskonook and Lamb fires, following erosion or debris flow events. The approach used for the follow-up studies did consider a wider range of soil properties, including water repellency. Because of limited resources, however, the assessments were restricted to easily accessible areas where potential elements at risk were identified. Based on the experience in completing post-fire assessments of the 2003 fires, it was recognized that:

- some assessment of fire severity, or vegetation severity, is an essential first step;
- there is very little background information on the extent of water repellency in the Southern Interior Forest Region, its occurrence relative to differing forest types, its occurrence on fires of differing severity, etc. (see Curran et al (2006) for a full list);
- the "from the road" assessments were, at best, a professional rough estimate; however, a more systematic approach is needed.

From both the 2003 fires and the 2004 Town Creek fire, it became obvious that many fires in the Southern Interior Forest Region were not of high severity, and vegetation recovery could be rapid after a fire. However, there is an obvious requirement to collect data from all fires so that staff can develop a useful database.

As a result of the work undertaken on these fires, the SIFR staff has gained a better appreciation of the significance of the post-wildfire impacts, such as the importance of understanding burn severity, the need for standard methods to assess for changes in water repellency and the establishment of a standard procedure for hazard and risk assessment. It is also apparent that there is a need for further research into many of the post-wildfire issues. There have been preliminary discussions with the US Forest Service regarding the opportunity to apply the WEPP model on wildfires in the SIFR and also to share information on the use of remote sensing as a tool to assess burn severity.

It is recommended that SIFR staff be encouraged to:

- Apply the Risk Assessment Procedure to future fires to determine post-fire risks and identify where improvements maybe required.
- Test the WEPP model currently used by the US Forest Service to assess post-wildfire impacts in selected areas of the SIFR to assess the validity and usefulness of the model in the southern areas of the SIFR.

- Continue research into the practical means to assess water repellency of burned areas in the BC Interior.
- Initiate research to understand the conditions that result in post-wildfire water repellency and the persistence of the condition in burned over areas.
- Initiate research to determine if there are “design” rainstorms that can be used as part of the hydrologic assessment in the risk assessment procedure.
- Pursue the development of remote sensing as a tool to assess burn severity.
- Continue to develop a close working relationship with counterparts in the US Forest Service in the western United States to share knowledge and expertise to improve the post-wildfire risk assessment process.

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Appendix

Peak Flow Models

Distributed Hydrology Soil Vegetation Model²

Description

The Distributed Hydrology Soil Vegetation Model was originally developed in the early 1990s by Mark Wigmosta while at the University of Washington, the model code has been further developed by a wide cast of characters at the University of Washington and at Pacific Northwest National Laboratory.

DHSVM is a distributed hydrologic model that explicitly represents the effects of topography and vegetation on water fluxes through the landscape. It is typically applied at high spatial resolutions on the order of 100 m for watersheds of up to 10⁴ km² and at sub-daily timescales for multi-year simulations. It has been applied predominantly to mountainous watersheds in the Pacific Northwest in the United States.

DHSVM is a research model and as such is continuously under development. Only very limited efforts have been paid to make a user-friendly interface. Its source code is available to interested parties, but be advised that no technical support is available other than that provided at the website <http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/>, unless specific arrangements are made.

Hardware requirements

The hardware requirements for DHSVM depend on the size of the application, that is, the number of pixels within the watershed. However, most modern workstations with a large amount of memory (512Mb RAM or more) and a fast processor (Pentium IV, PowerPC G4, or equivalent) will be amply sufficient.

DHSVM does not make use of multiple processors, so a fast single processor machine will result in a shorter runtime than a slower multi-processor machine (assuming no other processes are active).

Compiling and running the source code

DHSVM is written in ANSI-C, and will run under most operating systems. It has been successfully implemented on Pentium PC based systems (under FreeBSD, Linux, and Microsoft Windows), Apple PowerPC based systems (OS X), SUN workstations, and HP workstations.

The Gnu C-Compiler (gcc) is available for all these platforms and operating systems and is the compiler of choice. This means that this is the only compiler used in testing the model codes, and no attempts will be made to support other compilers.

You will need to modify the makefile that comes with the DHSVM source code to reflect the location of the necessary header and library files on your system. DHSVM has an option to display its output in an X-window while the model is running. This requires the availability of the X11 library on your system. To compile the code for the X-window display, uncomment the line in the makefile with `DEFS=-DHAVE_X11`.

Similarly, DHSVM can read and write NetCDF files. This option is only available if you have the netcdf libraries on your system. To download the netcdf software and obtain more information, visit the [Unidata website](#). To compile the code for reading and writing NetCDF files, uncomment the line in the makefile with `DEFS=-DHAVE_NETCDF`.

² The information provided in the section has been selected from the University of Washington website; <http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/>

Input Requirements

As a spatially distributed hydrological model, DHSVM is input intensive. In broad terms, the following input is needed for the implementation of the model in a specific area:

- Digital Elevation Model (DEM) of the basin
- Soil textural and hydraulic information
- Vegetation information
- Meteorological conditions at a subdaily timestep, in particular precipitation, air temperature, humidity, wind speed, incoming shortwave radiation and incoming longwave radiation
- Information about the stream and road network (location, width, etc.)

Soil and vegetation information is needed at the same resolution as the resolution at which the model is implemented. For each pixel a soil and vegetation type is specified, and a lookup table is used to store the associated soil and vegetation properties.

The following input files are part of a DHSVM application. Some files are always required, but additional files may be needed depending on the options specified in the configuration file. This is specified in the description below:

- Configuration file
- Mask file (Note: 2-D data binary files are stored from NW->SE, incrementing across columns before down rows)
- DEM file
- Soil type file
- Soil depth file
- Vegetation type file
- Meteorological station file
- Meteorological map files
- PRISM files
- Shading parameter files
- Wind model files
- Stream/road class files
- Stream/road network files
- Stream/road map files
- Travel time file
- Unit hydrograph file

To initialize the model, a number of model state files are required as well:

- Soil state file
- Snow state file
- Interception state file
- Channel state file
- Hydrograph state file

Model Output

There are a number of different types of output that the model can produce. In short, the following possibilities are available:

- Default output (these files are always produced)
- Model state files
- Network flow files
- Travel time based hydrograph file
- Optional output files

EPA Storm Water Management Model (SWMM)³

Description

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps.

SWMM was first developed in 1971, and has since undergone several major upgrades since then. It continues to be widely used throughout the world for planning, analysis and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. The current edition, Version 5, is a complete re-write of the previous release. Running under Windows, SWMM 5 provides an integrated environment for editing study area input data, running hydrologic, hydraulic and water quality simulations, and viewing the results in a variety of formats. These include color-coded drainage area and conveyance system maps, time series graphs and tables, profile plots, and statistical frequency analyses.

This latest re-write of SWMM was produced by the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory in a joint development effort with CDM, Inc., a global consulting, engineering, construction, and operations firm.

Capabilities

SWMM accounts for various hydrologic processes that produce runoff from urban areas. These include:

- time-varying rainfall
- evaporation of standing surface water
- snow accumulation and melting
- rainfall interception from depression storage
- infiltration of rainfall into unsaturated soil layers
- percolation of infiltrated water into groundwater layers
- interflow between groundwater and the drainage system
- nonlinear reservoir routing of overland flow.

Spatial variability in all of these processes is achieved by dividing a study area into a collection of smaller, homogeneous sub-catchment areas, each containing its own fraction of pervious and impervious sub-areas. Overland flow can be routed between sub-areas, between sub-catchments, or between entry points of a drainage system.

SWMM also contains a flexible set of hydraulic modeling capabilities used to route runoff and external inflows through the drainage system network of pipes, channels, storage/treatment units and diversion structures. These include the ability to:

- handle drainage networks of unlimited size use a wide variety of standard closed and open conduit shapes as well as natural channels

³ The information provided in the section has been selected from the US Environmental Protection Agency website - <http://www.epa.gov/ednnrmrl/models/swmm/index.htm>.

- model special elements such as storage/treatment units, flow dividers, pumps, weirs, and orifices
- apply external flows and water quality inputs from surface runoff, groundwater interflow, rainfall-dependent infiltration/inflow, dry weather sanitary flow, and user-defined inflows
- utilize either kinematic wave or full dynamic wave flow routing methods
- model various flow regimes, such as backwater, surcharging, reverse flow, and surface ponding
- apply user-defined dynamic control rules to simulate the operation of pumps, orifice openings, and weir crest levels.

In addition to modeling the generation and transport of runoff flows, SWMM can also estimate the production of pollutant loads associated with this runoff. The following processes can be modeled for any number of user-defined water quality constituents:

- dry-weather pollutant buildup over different land uses
- pollutant washoff from specific land uses during storm events
- direct contribution of rainfall deposition
- reduction in dry-weather buildup due to street cleaning
- reduction in washoff load due to BMPs
- entry of dry weather sanitary flows and user-specified external inflows at any point in the drainage system
- routing of water quality constituents through the drainage system
- reduction in constituent concentration through treatment in storage units or by natural processes in pipes and channels

Applications

Since its inception, SWMM has been used in thousands of sewer and stormwater studies throughout the world. Typical applications include:

- design and sizing of drainage system components for flood control
- sizing of detention facilities and their appurtenances for flood control and water quality protection
- flood plain mapping of natural channel systems (SWMM 5 is a FEMA-approved model for NFPI studies)
- designing control strategies for minimizing combined sewer overflows
- evaluating the impact of inflow and infiltration on sanitary sewer overflows
- generating non-point source pollutant loadings for waste load allocation studies
- evaluating the effectiveness of BMPs for reducing wet weather pollutant loadings.

Support

There is no formal support offered for EPA SWMM. A SWMM Users Listserve, established by the University of Guelph, allows subscribers to ask questions and exchange information. To subscribe, send an email message to listserv@listserv.uoguelph.ca with the words "subscribe swmm-users" (without the quotes) in the body followed by your name.

Downloads

File	Date	Description	Size (Kbytes)
<u>epaswmm5_setup.exe</u>	10/19/2005	Self-extracting installation program for SWMM 5.0.006a.	2,190
<u>epaswmm5_manual.pdf</u>	10/25/2005	SWMM 5.0 Users Manual in Adobe PDF format. 249 pages.	3,330
<u>swmm4to5_setup.exe</u>	5/25/2005	Utility for converting SWMM 4 data files to SWMM 5 files. Version 1.2.	1,519
<u>epaswmm5_engine.zip</u>	10/19/2005	Source code for the SWMM 5.0.006a computational engine.	254
<u>epaswmm5_gui.zip</u>	10/19/2005	Source code for the SWMM 5.0.006a graphical user interface.	545
<u>epaswmm5_iface.zip</u>	5/20/2005	SWMM 5.0 Interfacing Guide	32
<u>epaswmm5_qa.zip</u>	10/6/2005	Quality Assurance report for dynamic wave flow routing.	2,691
<u>epaswmm5_updates.txt</u>	10/19/2005	List of SWMM 5.0 updates and bug fixes.	18

Links

[EPA's Center for Exposure Assessment Modeling \(CEAM\)](#): The EPA Center for Exposure Assessment Modeling (CEAM) was established in 1987 to meet the scientific and technical exposure assessment needs of the United States Environmental Protection Agency (U.S. EPA) as well as state environmental and resource management agencies. CEAM provides proven predictive exposure assessment techniques for aquatic, terrestrial, and multimedia pathways for organic chemicals and metals.

[EPA's Multimedia Integrated Modeling System \(MIMS\)](#): Successfully modeling cross-media ecosystems entails solving a number of scientific and computational challenges, such as ensuring that consistent assumptions are used at the boundary of the media and managing the large number of models and data sets that are typically required. EPA's Multimedia Integrated Modeling System (MIMS) project is researching and developing solutions for some of those challenges.

[SWMM at OSU's College of Engineering](#): Version 4.4h of SWMM, maintained and enhanced by Prof. Wayne Huber and CDM, is available from this site.

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Hydrologic Modeling System – HEC-HMS⁴

Description

The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

The program is a generalized modeling system capable of representing many different watersheds. A model of the watershed is constructed by separating the hydrologic cycle into manageable pieces and constructing boundaries around the watershed of interest. Any mass or energy flux in the cycle can then be represented with a mathematical model. In most cases, several model choices are available for representing each flux. Each mathematical model included in the program is suitable in different environments and under different conditions. Making the correct choice requires knowledge of the watershed, the goals of the hydrologic study, and engineering judgment.

The program features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. A graphical user interface allows the seamless movement between the different parts of the program. Program functionality and appearance are the same across all supported platforms.

HEC-HMS provides a variety of options for simulating precipitation-runoff processes. In addition to unit hydrograph and hydrologic routing options similar to those in HEC-1, capabilities currently available include: a linear-distributed runoff transformation that can be applied with gridded (e.g., radar) rainfall data, a simple "moisture depletion" option that can be used for simulations over extended time periods, and a versatile parameter optimization option. The latest version also has capabilities for continuous soil moisture accounting and reservoir routing operations.

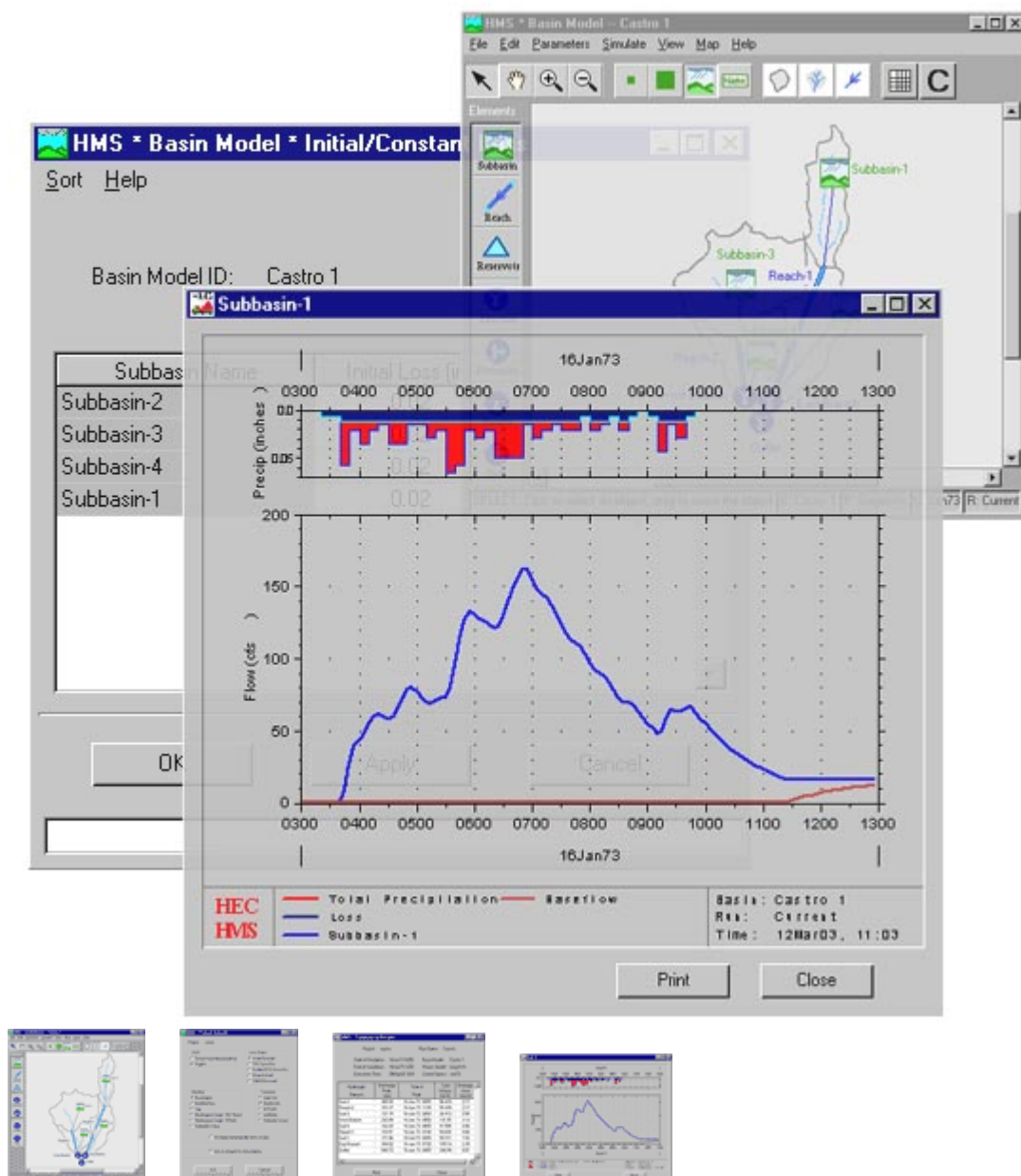
Hardware/Operating System Requirements

Any IBM or compatible machine with an 80386 processor or higher (an 80486 or higher is recommended). A hard disk with at least 15 megabytes of free space (20 megabytes or more is recommended). A CD-ROM drive. A minimum of 16 megabytes of RAM. A mouse. Color VGA or better video display (recommend running in Super VGA or higher). MS Windows 95, or MS Windows NT version 3.51 or higher.

Features

HEC-HMS is comprised of a graphical user interface (GUI), integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities. The Data Storage System, HEC-DSS, is used for storage and retrieval of time series, paired-function, and gridded data, in a manner largely transparent to the user.

⁴ The information provided in the section has been selected from the Water Resources Consulting Services website; <http://www.waterengr.com/HECHMS.html>



The Graphical User Interface (GUI) provides a means for specification of watershed components, inputting data for the components, and viewing the results. The GUI has capability for schematic representation of a network of hydrologic elements (e.g. sub-basins, routing reaches, junctions, etc.). You can configure the schematic by selecting and connecting icons that represent the elements. Once a schematic is developed, pop-up menus can be invoked from the element icons. A menu provides access to an editor for entering or editing data associated with the hydrologic element, and enables display of results of a simulation for that element. The GUI also contains global editors for entering or reviewing data of a given type (e.g., values for Green & Ampt parameters) for all applicable elements.

The results of the active run can be viewed and printed in tabular or graphical form. Three types of tabular data are available: (1) a master summary table with a single line of information for each hydrologic element, (2) an element summary table with information

tailored to the element type, and (3) an element time series table that shows results for each time interval. A graphical display is also available for each element type.

Technical Capabilities

The basic framework for simulation of basin runoff is similar to that in HEC-1. You can also import data from an HEC-1 input file. Hydrologic elements are arranged in a dendritic network, and computations are performed in an upstream-to-downstream sequence. Computations are performed with SI (Système International d'Unités) units. However you can enter input and view output with units in the U.S. Customary system, and can readily convert input/results from one unit system to the other.

The execution of a simulation, called a "run", requires specification of three sets of data. The first, labeled Basin Model, contains parameter and connectivity data for hydrologic elements. Types of element are: sub-basin, routing reach, junction, reservoir, source, sink, and diversion. The second set, labeled Precipitation Model, consists of meteorological data and information required to process it. The model may represent historical or hypothetical conditions. The third set, labeled Control Specifications, specifies time-related information for a simulation. A Project is used to hold the different data sets and can contain many of each type.

The program is multi-platform capable, meaning it operates on more than one kind of computer operating system. The CD-ROM versions contain executable files and installation instructions for Windows XP/2000/NT/98/95 systems.

Watershed Physical Description

The physical representation of a watershed is accomplished with a basin model. Hydrologic elements are connected in a dendritic network to simulate runoff processes. Available elements are: sub-basin, reach, junction, reservoir, diversion, source, and sink. Computation proceeds from upstream elements in a downstream direction.

An assortment of different methods is available to simulate infiltration losses. Options for event modeling include initial constant, SCS curve number, gridded SCS curve number, exponential, and Green Ampt. The one-layer deficit constant method can be used for simple continuous modeling. The five-layer soil moisture accounting method can be used for continuous modeling of complex infiltration and evapotranspiration environments. Gridded methods are available for both the deficit constant and soil moisture accounting methods.

Several methods are included for transforming excess precipitation into surface runoff. Unit hydrograph methods include the Clark, Snyder, and SCS techniques. User-specified unit hydrograph or s-graph ordinates can also be used. The modified Clark method, ModClark, is a linear quasi-distributed unit hydrograph method that can be used with gridded meteorologic data. An implementation of the kinematic wave method with multiple planes and channels is also included.

Multiple methods are included for representing baseflow contributions to subbasin outflow. The recession method gives an exponentially decreasing baseflow from a single event or multiple sequential events. The constant monthly method can work well for continuous simulation. The linear reservoir method conserves mass by routing infiltrated precipitation to the channel.

A variety of hydrologic routing methods are included for simulating flow in open channels. Routing with no attenuation can be modeled with the lag method. The traditional Muskingum method is included along with the straddle stagger method for simple approximations of attenuation. The modified Puls method can be used to model

a reach as a series of cascading, level pools with a user-specified storage-discharge relationship. Channels with trapezoidal, rectangular, triangular, or circular cross sections can be modeled with the kinematic wave or Muskingum-Cunge methods. Channels with overbank areas can be modeled with the Muskingum-Cunge method and an 8-point cross section.

Water impoundments can also be represented. Lakes are usually described by a user-entered storage-discharge relationship. Reservoirs can be simulated by describing the physical spillway and outlet structures. Pumps can also be included as necessary to simulate interior flood area. Control of the pumps can be linked to water depth in the collection pond and, optionally, the stage in the main channel.

Meteorology Description

Meteorologic data analysis is performed by the meteorologic model and includes precipitation, evapotranspiration, and snowmelt. Six different historical and synthetic precipitation methods are included. Two evapotranspiration methods are included at this time. Currently, only one snowmelt method is available.

Four different methods for analyzing historical precipitation are included. The user-specified hyetograph method is for precipitation data analyzed outside the program. The gage weights method uses an unlimited number of recording and non-recording gages. The Thiessen technique is one possibility for determining the weights. The inverse distance method addresses dynamic data problems. An unlimited number of recording and non-recording gages can be used to automatically proceed when missing data is encountered. The gridded precipitation method uses radar rainfall data.

Four different methods for producing synthetic precipitation are included. The frequency storm method uses statistical data to produce balanced storms with a specific exceedance probability. Sources of supporting statistical data include Technical Paper 40 and NOAA Atlas 2. While it was not specifically designed to do so, data can also be used from NOAA Atlas 14. The standard project storm method implements the regulations for precipitation when estimating the standard project flood. The SCS hypothetical storm method implements the primary precipitation distributions for design analysis using Natural Resources Conservation Service (NRCS) criteria. The user-specified hyetograph method can be used with a synthetic hyetograph resulting from analysis outside the program.

Potential evapotranspiration can be computed using monthly average values. There is also an implementation of the Priestley-Taylor method that includes a crop coefficient. A gridded version of the Priestley-Taylor method is also available.

Snowmelt can be included for tracking the accumulation and melt of a snowpack. A temperature index method is used that dynamically computes the melt rate based on current atmospheric conditions and past conditions in the snowpack.

Hydrologic Simulation

The time span of a simulation is controlled by control specifications. Control specifications include a starting date and time, ending date and time, and a time interval.

A simulation run is created by combining a basin model, meteorologic model, and control specifications. Run options include a precipitation or flow ratio, capability to save all basin state information at a point in time, and ability to begin a simulation run from previously saved state information.

Simulation results can be viewed from the basin map. Global and element summary tables include information on peak flow and total volume. A time-series table and graph are available for elements. Results from multiple elements and multiple simulation runs can also be viewed. All graphs and tables can be printed.

Parameter Estimation

Most parameters for methods included in subbasin and reach elements can be estimated automatically using optimization trials. Observed discharge must be available for at least one element before optimization can begin. Parameters at any element upstream of the observed flow location can be estimated. Six different objective functions are available to estimate the goodness-of-fit between the computed results and observed discharge. Two different search methods can be used to minimize the objective function. Constraints can be imposed to restrict the parameter space of the search method.

Analyzing Simulations

Analysis tools are designed to work with simulation runs to provide additional information or processing. Currently, the only tool is the depth-area analysis tool. It works with simulation runs that have a meteorologic model using the frequency storm method. Given a selection of elements, the tool automatically adjusts the storm area and generates peak flows represented by the correct storm areas.

GIS Connection

The power and speed of the program make it possible to represent watersheds with hundreds of hydrologic elements. Traditionally, these elements would be identified by inspecting a topographic map and manually identifying drainage boundaries. While this method is effective, it is prohibitively time consuming when the watershed will be represented with many elements. A geographic information system (GIS) can use elevation data and geometric algorithms to perform the same task much more quickly. A GIS companion product has been developed to aid in the creation of basin models for such projects. It is called the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) and can be used to create basin and meteorologic models for use with the program.

Documentation

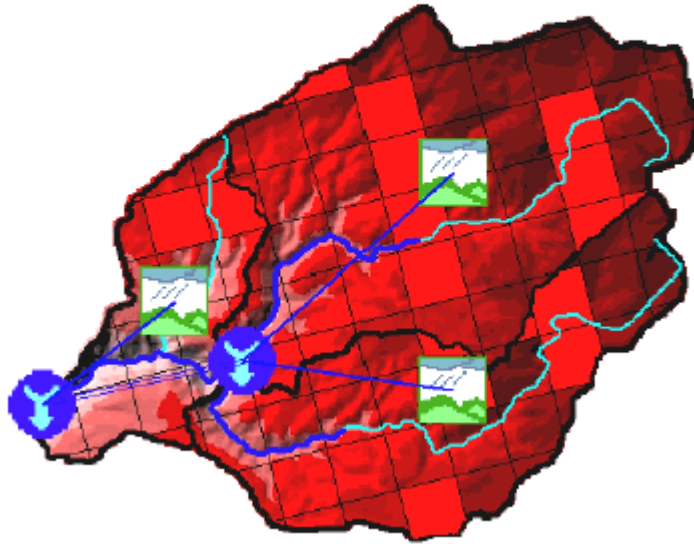
The program's revised User's Manual describes how to use program features. The program's Technical Reference Manual contains descriptive information on the mathematical models used in the program. A new Applications Guide for HEC-HMS is now also available. It completes the basic documentation set for the program. All manuals are provided in PDF file format for easy online viewing and self printing.

The Technical Reference Manual is currently being updated. The current manual continues to accurately describe the simulation methods in Version 3.0.0 even though the manual was not updated with the new release. However, new simulation methods added for Version 3.0.0 are not included in the manual. The updated manual will add information to the manual on all of the new simulation methods that have been added to the program. The updated manual will also expand the amount of information for each method. The goal is to provide complete information on the source and derivation of the equations used in each method. Information will also be provided on parameter estimation. Finally, numeric solution details will be provided on how the equations are solved inside the program.

The Applications Guide is currently being updated. The current manual continues to accurately describe how to incorporate hydrologic simulation into project work. However, Version 3.0.0 includes some new features that can make the work simpler to

perform. The manual also includes some screen pictures that are no longer accurate. The user should be careful to interpret the current manual in the context of interface changes made for Version 3.0.0. The updated guide will include accurate screen pictures and suggestions for better use of the program to conduct project work.

Geospatial Hydrologic Modeling Extension HEC-GeoHMS



HEC-GeoHMS, Version 1.1 for ArcView

The Geo-spatial Hydrologic Modeling Extension (HEC-GeoHMS) is a software package for use with the ArcView Geographic Information System. GeoHMS uses ArcView and Spatial Analyst to develop a number of hydrologic modeling inputs. Analyzing digital terrain information, HEC-GeoHMS transforms the drainage paths and watershed boundaries into a hydrologic data structure that represents the watershed response to precipitation. In addition to the hydrologic data structure, capabilities include the development of: grid-based data for linear quasi-distributed runoff transformation (ModClark), the HEC-HMS basin model, physical watershed and stream characteristics, and background map file.

HEC-GeoHMS provides an integrated work environment with data management and customized toolkit capabilities, which includes a graphical user interface with menus, tools, and buttons. The program features terrain-preprocessing capabilities in both interactive and batch modes. Additional interactive capabilities allow users to construct a hydrologic schematic of the watershed at stream gages, hydraulic structures, and other control points. The hydrologic results from HEC-GeoHMS are then imported by the Hydrologic Modeling System, HEC-HMS, where simulation is performed.

HEC-GeoHMS is now included on the HEC-HMS, HEC-Combo Pack or HEC-Works CDs (including all three Program Manuals in PDF format) at *no additional cost*.

Ship or Download the CD and Manuals

The HEC-HMS program is either distributed on CD or as a download. Both versions come with full program documentation in PDF file format. The CD version comes with a *free*

copy of HEC-1 and the NEW HEC-DSS Vue program. If you want to download the program yourself you can save all shipping costs. You will be given download instructions via e-mail upon receipt of payment.

PRICES:

Program and Manuals on CD - \$35

Download Program and Manuals - \$25

Water Erosion Prediction Project (WEPP) - FS WEPP Interfaces

Description

FS WEPP is a set of interfaces designed to allow users to quickly evaluate erosion and sediment delivery potential from forest, range, and roads. The erosion rates and sediment delivery are predicted by the Water Erosion Prediction Project (WEPP) model, using input values for forest conditions developed by scientists at the Rocky Mountain Research Station. One of the newest interfaces is ERMIT, which predicts erosion probability after wildfire for unmitigated conditions as well as for various treatments.

WEPP

The Water Erosion Prediction Project (WEPP) soil erosion model is being developed by an interagency group of scientists including the USDA's Forest Service, Agricultural Research Service, and Natural Resources Conservation Service, and the Department of Interior's Bureau of Land Management and Geological Survey. Scientists from these agencies throughout the United States have been working since 1985 to develop WEPP to replace the Universal Soil Loss Equation (USLE).

The WEPP model is a complex computer program that describes the processes that lead to erosion. These processes include infiltration and runoff; soil detachment, transport, and deposition; and plant growth, senescence, and residue decomposition. For each day of simulation, WEPP calculates the soil water content in multiple layers and plant growth/decomposition. The effects of tillage processes and soil consolidation are also modeled.

WEPP can be run from an MS DOS set of input screens or from a Windows interface (continuously being modified and updated). In both versions, a set of file builders assists the user in building or altering input files that can include more than 400 input variables for a single run. WEPP can be accessed on-line at

<http://forest.moscowfsl.wsu.edu/fswepp/>

Climate Modeling

For details on using the FS WEPP climate interface refer to the document Enhancements to the CLIGEN Weather Generator for Mountainous or Custom Applications by Scheele, D.L.; Elliot, W.J.; Hall, D.E that is available at the following website

<http://forest.moscowfsl.wsu.edu/engr/library/Elliot/Elliot2001e/2001e.html>,

and is reproduced below.

Introduction

The single most important factor impacting soil erosion is weather. Weather is highly variable from year to year, and site to site, particularly when the sites are at different elevations, or on opposite sides of a mountain range. The better the weather can be predicted for a given site, the better will be the predicted erosion for that site.

The Water Erosion Prediction Project (WEPP) model is a process-based soil erosion model developed to replace the Universal Soil Loss Equation. WEPP requires a daily climate input to drive the plant growth, hydrologic, and soil erosion routines (Flanagan and Livingston 1995). A daily stochastic weather generator, CLIGEN, is packaged with WEPP. Accompanying CLIGEN is a database of weather statistics for about 1100 climates, one for every 60-mile grid across the U.S. (Nicks et al. 1995).

The 60-mile grid of climates was acceptable for areas in the central U.S. where there are minimal differences in weather from one station to the next. In mountainous areas, however, the database was inadequate. Precipitation and temperatures vary considerably with elevation and aspect. Most weather stations in the CLIGEN database were located in valleys, and so gave unacceptably dry and warm climates for nearby mountainous areas. WEPP users sometimes want to incorporate the weather at the remote site with records from SNOTEL stations or data collected as part of other short-term studies.

Another problem with the CLIGEN generator was encountered during some WEPP runs in which a generated climate file predicted more than 999.9 mm of precipitation in a single day, for a climate with an annual precipitation of about 500 mm. The source of this error was a precipitation skew coefficient value that was about 4 times the amount of most skew coefficients in the input statistics data set.

While the above problems were being identified, we were developing a new suite of Internet-based interfaces for WEPP to help users predict soil erosion from roads, forests, and rangelands (Elliot et al. 2000). Included with those interfaces was the need to develop a complementary climate generator interface.

In 1999, Oregon State University, in cooperation with the Natural Resource Conservation Service and numerous state climatologists, released the PRISM database of monthly precipitation values for a 2.5 min (4 km) grid covering the continental U.S. (Daly et al. 1997). The PRISM database, with monthly precipitation estimates for more than 900,000 locations, could enhance the CLIGEN database.

The objectives of this paper are to:

- Describe the corrections and improvements made to the CLIGEN database;
- Discuss the techniques and assumptions for allowing customization of the database;
- Describe accessing the PRISM database to aid in climate customization; and
- Describe the Internet interface technology.

Corrections

CLIGEN generates a stochastic weather sequence from a set of climate statistics called parameter files, for the station selected. The CLIGEN parameter files list monthly statistical values for precipitation, temperature, dew point, solar radiation, and wind information. The parameter files were developed from five databases containing summaries of weather station observations. Some of the fields in these five databases contained errors that were transferred to the parameter files when they were generated. We corrected the errors in the databases, added stations to the databases, and rebuilt the parameter files. In a comparison of the old and new parameter files, we found that about ten percent of the parameter files had at least one major error that had been corrected. The corrections include:

- Changes to 16 station names;
- Corrections of 5 latitudes, 14 longitudes, and 33 elevations;
- Changes to 329 time to peak intensity mean values; and
- Changes to about 600 wind values, mostly from changes in one of the station summary files.

Some were direct changes, some changed because different stations were used for interpolation, and some changed due to changes in the program that created the CLIGEN parameter files. Many of the corrections made were from comparisons of the CLIGEN weather station database to the 1991 station data inventory files obtained from the Western Regional Climate Center website (WRCC 1991). The five CLIGEN weather

databases contained enough data to increase the number of CLIGEN stations from 1100 to about 2600, covering the Continental U.S., Alaska, Hawaii, Pacific Islands, and the territory of Puerto Rico. Along with the corrections and increased sites, a list was added to the end of each parameter file to report the stations used for interpolation of values and their weighting factors.

Customization

Generally, users who wish to customize a climate have knowledge of mean precipitation or temperatures for a given site. They seldom have enough information to develop values for standard deviation or skew statistics. Hence, a technology was developed to allow users to customize the mean values for the site of interest, while using the other statistics from the nearest CLIGEN station. In early attempts to develop customized climates, a set of instructions was developed describing how to modify the parameter file to better match the desired climate. This arduous process involved changing statistics in the fixed-format parameter file, and proved to be too difficult for most users. A new interface was developed, which, as a minimum, allowed users to enter the average monthly precipitation amounts. Users can either change individual monthly values, or specify a percent increase or decrease to be applied across the year. If they have the data, users can specify the number of wet days in a month, and the average monthly maximum and minimum temperatures. The values for the number of wet days in each month are used as an input value to obtain the wet day probabilities for the climate station. CLIGEN requires the probability of a wet day following a wet day ($P(W|W)$) and the probability of a wet day following a dry day ($P(W|D)$). For our interface, the number of wet days is used because it is more readily available. The probability of a wet day in a given month, $P(W)$, can be calculated by dividing the number of wet days by the number of days in the month. The relationship between the three probabilities is:

$$P(W) = P(W|W) P(W|W) + (1 - P(W|W)) P(W|D) \quad (1)$$

Equation 1 can be solved for any of the three variables, so if two are known or assumed, the third can be calculated. As the CLIGEN parameter file requires $P(W|W)$ and $P(W|D)$, and the user provides only $P(W)$, some assumptions were necessary about the relationship between $P(W|W)$ and $P(W|D)$. Geng et al. (1986) have recommended using:

$$P(W|D) = 0.75 P(W) \quad (2)$$

so

$$P(W|W) = 0.25 + P(W|D) \quad (3)$$

However, the result of using these two equations is a value of $P(W|W)$ always greater than 0.25, which from the CLIGEN data set is not always true, especially in the drier climates. Other attempts to fix the value for either $P(W|W)$ or $P(W|D)$ were found to be unsatisfactory as the values could result in negative probabilities in drier climates, or probabilities greater than one in wetter climates. To overcome these problems, the ratio of $P(W|D):P(W|W)$ was determined from the nearby CLIGEN parameter file, and that ratio combined with the user's value for $P(W)$ to derive $P(W|W)$ and $P(W|D)$ for the desired climate. Substituting *Ratio* for $P(W|D)/P(W|W)$ in equation 1 and rearranging then gives:

$$P(W|W) = 1/(1 - \text{Ratio} + (\text{Ratio} / P(W))) \quad (4)$$

and

$$P(W|D) = P(W|W) * \text{Ratio} \quad (5)$$

The new interface incorporates the option to modify temperatures by lapse rate. The lapse rates were specified as 6°C/km for maximum temperature and 5°C/km for minimum temperature. These values are comparable to 4.8 to 6.8°C/km found by Johnson et al. (1998) and the average 6°C/km given by Trewartha and Horn (1980). Generally, minimum temperature lapse rates are not as great as maximum rates because of temperature inversions that can occur during the evenings or during very cold winter days.

PRISM

The PRISM (Parameter-Regressions on Independent Slopes Model) database was developed cooperatively by the USDA-NRCS and ARS, and Oregon State University (Daly et al., 1997). The database contains the average monthly precipitation values and average elevations for a 2.5-min. grid covering the entire continental U.S. It was developed by interpolating and extrapolating precipitation amounts between weather stations. Factors to allow for elevation, aspect, and other local effects were considered in the development. Numerous state climatologists have reviewed the PRISM database, and their observations have been incorporated into it. Figures 1 and 2 present some typical results in monthly precipitation distributions for Moscow, ID, and Cowetta, NC. The database was installed on our file servers, and an interface was developed to aid in finding the desired grid on the database.

Interface

We are developing Internet interfaces for the WEPP model (<http://forest.moscowfsl.wsu.edu/fswepp>) (Elliot et al. 2000). Included in these WEPP interfaces is one that allows the selection and modification of climates for use within the interfaces, and another for generating and downloading climates for use with either the MS DOS or Windows versions of the WEPP model. The interface called Rock Clime is a series of web pages to aid the user in selecting a state, and then a climate station. The user can then modify the monthly precipitation amounts manually or with the aid of PRISM. He or she can allow the interface to adjust the maximum and minimum temperatures by a lapse rate, or manually specify the monthly values. Figure 3 shows the web page where the manual adjustments are made, and figure 4, the page where the PRISM grid can be selected.

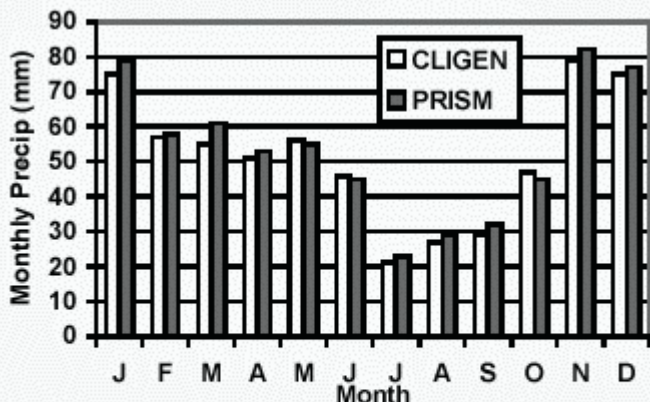


Figure 1. Monthly distribution of precipitation from the CLIGEN database, and the PRISM grid for Moscow, ID.

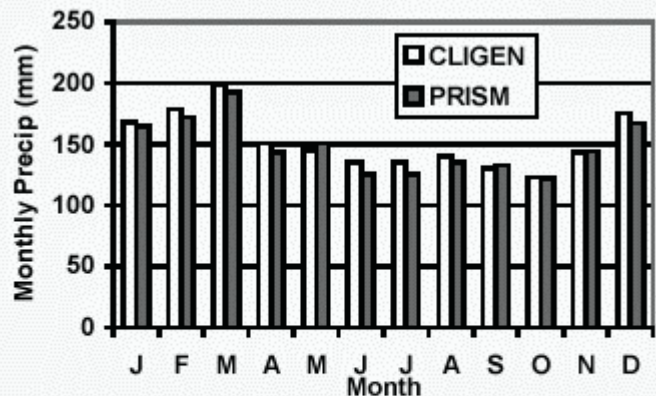


Figure 2. Monthly distribution of precipitation from the CLIGEN database, and the PRISM grid for Cowetta, NC.

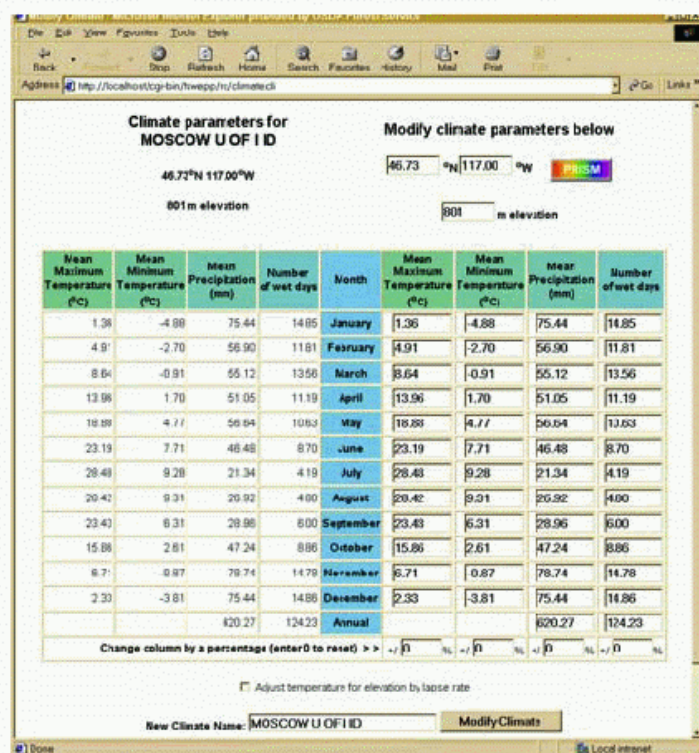


Figure 3. Climate modification page in Rock Clime interface.

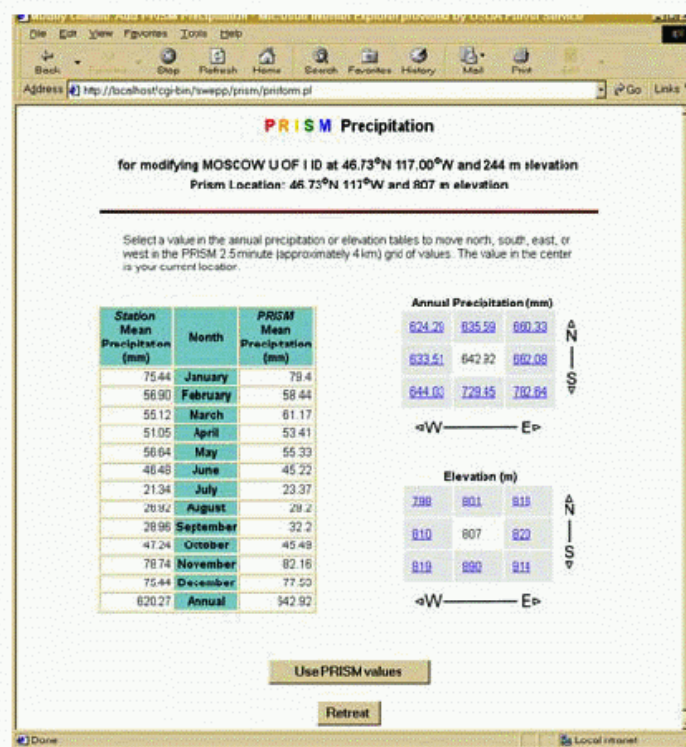


Figure 4. PRISM grid selection page in Rock Clime interface.

Summary

To better predict soil erosion, this paper described corrections made to the CLIGEN database. It then presented the assumptions necessary to allow users to generate a custom climate, including estimations of the probabilities associated with a wet day and lapse rates for temperature adjustments. The PRISM precipitation database was also incorporated into the technology, and a series of Internet web pages was developed to link the enhanced climate database to either standalone versions of the WEPP model, or to the Forest Service Internet WEPP interface.

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USDA Forest Service, Rocky Mountain Research Station, Moscow Forestry Sciences Laboratory

<http://forest.moscowfsl.wsu.edu/>